AFIT/GE/ENG/00M-05

EVALUATION OF A METHOD FOR
KINEMATIC GPS CARRIER-PHASE
AMBIGUITY RESOLUTION USING A
NETWORK OF REFERENCE RECEIVERS

THESIS

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Preface

Working on this thesis has been the highlight of my academic career. As much fun as it has been, I am very glad it is now over. There are many people who have helped me along the way.

First, and most importantly, I must thank my wife Crystal ---- profusely. She has been the most supportive wife and wonderful mother to our four children that I could have ever dreamed of. I owe her a long, relaxing vacation wherever she wishes.

My four children; Evan, Miranda, Quinn, and Elora. You give meaning to all I do and a purpose for it all.

Without a doubt, I owe a lifelong debt of gratitude to my fellow controls students; Paul Henderson, Todd Broaddus, and Mike Presnar. The crick in their backs should be going away soon, as they will no longer have me to carry along. Many thanks to all three of you for sharing your knowledge, support, and lives with me these past 18 months.

Of course, I would also like to thank my thesis advisor Captain John Raquet and readers, Doctor Peter Maybeck and LtCol Mikel Miller. It was Captain Raquet's doctoral research that my thesis is based on. Without the original ideas of people like him; factories become idle, cities remain unbuilt, and countries fade away. Thank you very much for letting me extend your vision.

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Abstract

New applications for GPS have driven a demand for increased positioning accuracy. The emerging GPS technology particularly affects the test community. The testing equipment and method must provide a solution that is an order of magnitude more precise than the tested equipment to achieve the desired accuracy. Carrier-phase differential GPS methods using a network of reference receivers can provide the centimeter-level accuracy required over a large geographical area.

This thesis evaluates the performance of a 5-receiver network over a 50 km x 120 km area of New Mexico, using a GPS network algorithm called NetAdjust. The percentage of time a fixed integer solution was available for a kinematic baseline was investigated for three types of measurements.

Results showed that the virtual reference receiver method using NetAdjust-corrected measurements outperformed the raw and NetAdjust-corrected file results. However, these results were only obtained for the shortest baseline receivers. The receivers with longer baselines did not experience the same degree of success, but did lead to several important insights gained from the research. Most importantly, the accuracy of the reference receiver coordinates is critical to the performance of a reference receiver network. Further testing must be accomplished before a full implementation is recommended.

EVALUATION OF A METHOD FOR KINEMATIC GPS CARRIER-PHASE AMBIGUITY RESOLUTION USING A NETWORK OF REFERENCE RECEIVERS

1. Introduction

1.1. Background

The use of the Global Positioning System (GPS) is spreading daily in general use and into all types of new commercial and military applications. As the importance of the system has steadily increased since achieving initial operating capability in December 1993, tremendous levels of funding have been spent developing new applications, and a demand for increased accuracy has risen. In response to this demand the U.S. government has promised to remove the Satellite Availability (SA) from the Standard Positioning Service (SPS) signal by 2006. This will yield significant accuracy improvements to the civilian GPS user. Instead of the predictable accuracy of 100 meters (2drms, 95%) achievable by SPS, users will now have access to the formerly restricted Precise Positioning Service (PPS) which has a predictable accuracy of 22 meters (2drms = 2 *x* drms, 95%) [1]. The distance root mean square (or drms) notation is a common navigation measure. Two times the drms (2 *x* drms, 95%) value is the radius of a circle in which 95% of all possible points lie within. While waiting for SA to be removed, civilian users have found a variety of ways to obtain increased position accuracy.

Many commercial applications have incorporated Differential GPS (DGPS) techniques in order to obtain greater positional accuracy. The two types of DGPS

positioning that may be performed are static and kinematic. All receivers are placed in fixed locations for static positioning. Kinematic positioning involves a fixed reference receiver and a mobile receiver. Offshore oil exploration and the land surveying community are two prime examples of commercial applications that incorporate high-accuracy DGPS techniques. The most accurate of these techniques use the accumulated phase measurement of the GPS carrier signal to calculate the relative position between two receivers and reduce the correlated measurement errors. In contrast, the United States Air Force has been slow to adopt DGPS. One reason is that military applications did not require the improved accuracy provided by DGPS due to their access to the PPS or P-code measurements. This is beginning to change, as increasingly more potential military applications require a level of accuracy that can only be obtained by incorporating DGPS techniques with the P-code measurements. In addition, this accuracy ideally needs to be available over a wide area with a minimal number of GPS receivers.

One military community that needs access to extremely accurate position measurements is the test community. The 746th Test Squadron (746th TS) at Holloman Air Force Base, New Mexico conducts extensive testing of government GPS, Inertial Navigation System (INS), and embedded GPS/INS equipment. Home of the Central Inertial Guidance Test Facility (CIGTF), a critical component of the squadron's ability to provide customers with the highest quality test and evaluation data is highly accurate knowledge of a "truth" position against which test item accuracy can be measured. In order to provide this type of accuracy to users, the truth position of the test equipment should have at least an order of magnitude greater accuracy than the test item. As the

GPS equipment under test becomes more accurate with advances in both hardware design and software algorithms, it is necessary to increase the accuracy of the testing equipment. This becomes much more difficult when dropping down to the centimeter and sub-centimeter levels of accuracy. Incorporating a network of reference receivers and using the NetAdjust method ([2],[3],[4],[5]) provides an improved solution that will be input into the CIGTF High Accuracy Post-processing reference System (CHAPS) [6]. The improved accuracy provided by the NetAdjust algorithm allows CHAPS to maintain an order of magnitude greater accuracy than GPS test items.

1.2. Problem Definition

In two previous receiver networks tested, the NetAdjust method has proven to be an effective method of ambiguity resolution. Ambiguity resolution is the process in which the fixed integer ambiguity values necessary to perform high accuracy carrier-phase positioning are determined. The goal herein is to apply the NetAdjust method on actual data from a test receiver network at the White Sands Missile Range (WSMR) and prove the method is capable of providing increased availability and reliability of ambiguity resolution. The increased availability and reliability will lead to greater precision over longer baselines (typically those greater than 30 km). This provides a direct benefit to the 746th TS by increasing the accuracy of test assets. A more in-depth discussion on the significance of long baselines is included shortly.

Figure 1-1 shows the desired GPS receiver network structure. Few receivers are required over a large area, yet centimeter level positioning accuracy is attainable anywhere inside the network. This is in stark contrast to Figure 1-2 where multiple

independent receivers are used over the same total area to obtain the same accuracy using standard DGPS techniques.

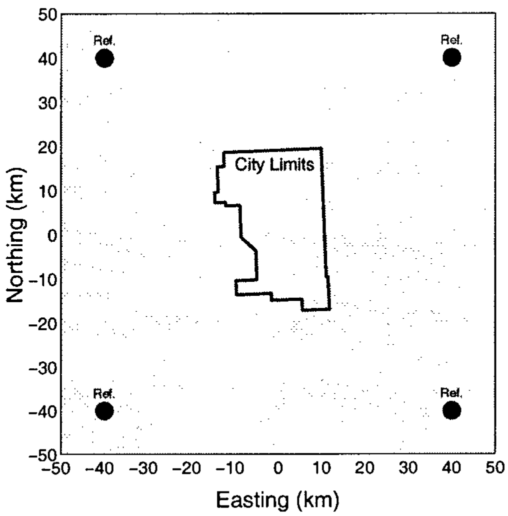

Figure 1-1. Desired network requires few receivers to cover total area.

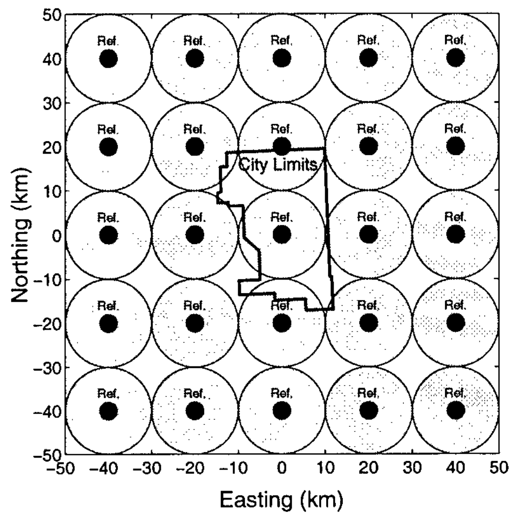

Figure 1-2. Many independent receivers required to cover same total area.

There are many challenges to implementing a system with centimeter level accuracy over long baselines. To establish this accuracy, the carrier-phase integer ambiguities must be resolved. Ambiguities are easily resolved over short baselines, but as the distance between two receivers increases, ambiguity resolution becomes increasingly difficult to accomplish since atmospheric errors decorrelate over distance. In order to resolve the ambiguities successfully over longer baselines, if it is possible at all, data must be recorded for longer time periods. This in turn increases the amount of computer processing time required. Ideally, the least amount of data possible is used to resolve ambiguities with long baselines. Standard DGPS techniques by themselves will not completely satisfy accuracy desires. A method to improve the availability and reliability to resolve carrier-phase ambiguities is required. The NetAdjust method [2] is one that has shown great promise in these areas.

1.3. Scope

The scope of this thesis is confined to all issues that assist the 746th TS at Holloman Air Force Base, New Mexico in obtaining more accurate truth data during kinematic carrier-phase positioning tests. Kinematic carrier-phase positioning involves one or more reference receivers on the ground and a mobile receiver in either an aircraft or some type of vehicle. The thesis focuses on the potential of implementing a network of reference receivers across the WSMR and the advantages it could provide to the 746th TS. This is accomplished by collecting and post-processing data from each reference receiver and applying the NetAdjust method to calculate the increases in availability and reliability of ambiguity resolution over individual kinematic baselines. The potential of implementing a virtual reference receiver concept is investigated as well

This thesis does not address a method of transmitting reference receiver data to a central location automatically for processing. The thesis also does not involve developing any methods for conducting real-time carrier-phase ambiguity resolution. Each of these would be a topic for follow-on research.

1.4. Other Research

Previous research published by Raquet [2,3,5] tested the NetAdjust method on an 11-receiver network covering a 400 km x 600 km region in southern Norway. Seven different test receiver networks of varying baseline length were used to evaluate NetAdjust performance. As the baseline length between the reference and remote receivers increased, the presence of NetAdjust becomes more obvious. There was virtually no improvement gained from the application of NetAdjust for baselines under 30 km. Yet, for baselines above 200 km, NetAdjust reduced the phase double-difference

RMS error up to 50%. Phase double differencing will be covered later in Chapter 2.3. NetAdjust proved effective in reducing correlated phase errors such as atmospheric errors. L1 code position errors were reduced by an average of 28% regardless of baseline length. In addition, NetAdjust significantly enhanced the ability to resolve widelane carrier-phase integer ambiguities. Widelane measurements are obtained by differencing the L1 and L2 measurements (L1 measurement – L2 measurement). Use of the widelane measurement results in a more efficient ambiguity search due to the larger (86.25 cm) wavelength as opposed to 19.03 cm for L1 only and 24.42 cm for L2 only. Calculation of the widelane wavelength is shown in Equation (1-1):

$$\begin{aligned} f_{wl} &= 1575.42 - 1227.6 = 347.82\ MHz \\ \frac{c}{f_{wl}} &= \frac{3x10^8}{347.82x10^6} = 0.8625\ meters \end{aligned} \qquad \textbf{(1-1)}$$

The combination results in a hundredfold decrease in the number of integer-ambiguity set residuals that must be computed and examined during a given epoch [2]. Figure 1-3 and Figure 1-4 illustrate the marked improvement in the percentage of ambiguities fixed for seven separate baselines using widelane measurements as opposed to L1 measurements.

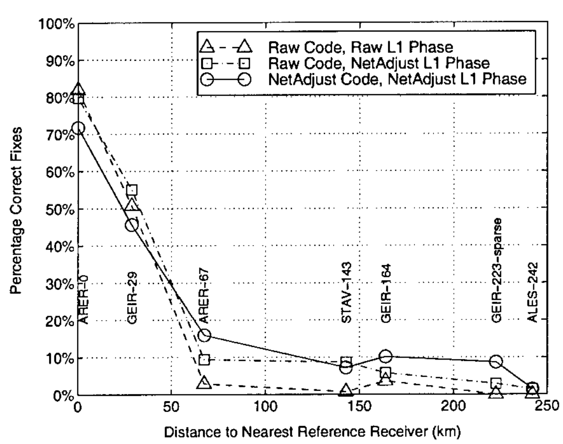

Figure 1-3. Percentage of correct fixes for L1 ambiguities.

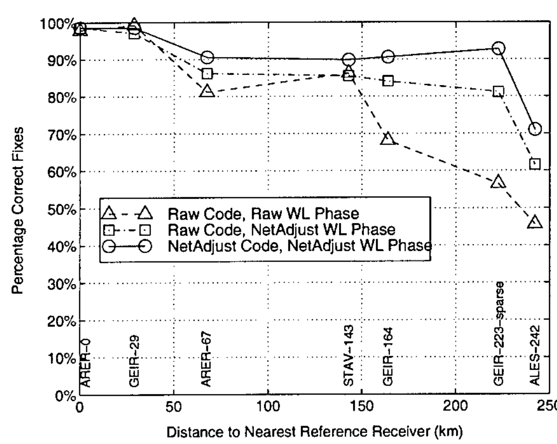

Figure 1-4. Percentage of correct fixes for Widelane ambiguities.

Other published research that covers objectives similar to this thesis is Van der Marel's work on virtual GPS reference receivers [7]. A network of five reference receivers was constructed in Holland to record data continuously and transmit hourly to a central computer. Users access data via a web interface and download "virtual" reference station data for any desired location within the network. The data for the virtual reference station imitates a real receiver at the desired location as best as possible.

Processing the data necessary to calculate the virtual reference station information is split into two steps. A free network adjustment of all the reference stations is performed first. Then the network-adjusted observations are used to fix the coordinates of one reference receiver, which accomplishes a baseline adjustment of the remote receiver. The user gets the benefit of data that gives comparable accuracy to a network solution when used to calculate a baseline solution. If users wisely choose a location near their area of interest, the baselines will be short and whatever established ambiguity resolution technique the user employs can be easily performed. However, performing a network adjustment on reference receiver coordinates calculated from a limited time interval of observations, as opposed to surveyed or otherwise known coordinates, will produce less accurate results.

1.5. Assumptions

Here are some known assumptions in this thesis:

a) All data is post-processed

b) No GPS jamming that would adversely affect the reference receiver network is present while recording data

c) All receivers are working within factory specifications

d) Satellite and receiver antenna phase center offsets are assumed to be zero

e) The test mission path is within the network of reference receivers

f) All calculations performed use the Earth-Centered Earth-Fixed (ECEF) frame and World Geodetic System 1984 (WGS-84) coordinates

1.6. Thesis Overview

Five chapters, two appendices, and an acronym list are included within this thesis.

Chapter 2 provides the necessary background to understand the terminology, basics of GPS, and hardware and software used during the thesis research. An overview of code and carrier-phase DGPS techniques is presented, along with discussion concerning the NetAdjust method and virtual reference receiver theory. The software programs used, Ashtech Office Suite (AOS) v2.0 [8] and MATLAB® v5.3 [10], and CHAPS [6] are also covered in detail.

Chapter 3 integrates the hardware and software discussed in Chapter 2 together in a methodology that ultimately results in a more accurate truth position solution. This solution addresses the problem faced by the 746th TS in maintaining its ability to test GPS equipment accurately.

In Chapter 4, the NetAdjust method and the virtual receiver concept are applied to a network of five receivers at WSMR. The results are analyzed to show the improvements in amount of time required resolve carrier-phase integer ambiguities and the percentage of ambiguities resolved for a kinematic DGPS case.

Chapter 5 lists conclusions on how effective a network of reference receivers installed at WSMR would be, what benefits there are to installing a network, and what needs to be accomplished for this to become reality for post-processed data at the 746th TS.

2. Background

2.1. Overview

This chapter introduces standard DGPS techniques and sources of GPS errors. Overviews of the NetAdjust algorithm and the virtual reference receiver concept are then presented. The commercial software packages used in this research are described as well.

2.2. DGPS

The standard DGPS technique described throughout this thesis uses two receivers. The base or reference receiver is located at a surveyed or otherwise known location. The remote receiver is at an unknown location at some distance from the reference receiver. This distance is commonly referenced as the baseline. A static baseline is one in which the remote receiver is fixed to one set of coordinates. Should the remote receiver be moving, the distance between the two receivers is called the kinematic baseline.

2.2.1. Sources of GPS Errors

The accuracy of each individual receiver's measurements is degraded by a combination of ionospheric and tropospheric delay, ephemeris prediction error, measurement noise, multipath, clock errors, and SA. However, incorporating DGPS techniques for two receivers separated by a short baseline, all of the errors (with the exception of multipath and measurement noise) are correlated, so they can be reduced or removed.

Placing two receivers next to each other ensures the signals received from the satellites orbiting overhead experience the exact same atmospheric effects. As the distance (baseline) increases between the two receivers, the atmosphere through which the satellite signals travel starts to change. The farther apart the receivers are placed, the

greater the difference in atmospheric effects experienced by the signals. This difference results in the errors decorrelating between the receivers. This decorrelation process also occurs with ephemeris prediction errors.

2.2.1.1. *Ionospheric Delay*

The dominant factor in the magnitude of ionospheric delay is solar activity. Other contributing factors include time of day, user location, satellite elevation angle, and scintillation (which all relate back to solar activity). Scintillation can cause the received signal amplitude and phase to fluctuate rapidly with time [11]. Overall, the ultraviolet light from the sun is the primary influence on the total electron content (TEC) in the atmosphere (which directly relates to signal delay). The highest levels of activity occur during midafternoon (around 1400 local) and the lowest levels near midnight (around 0200 local) [11]. The amount of error in GPS measurements attributed to ionospheric delay is mainly dependent on the time of day that data is recorded. The ionosphere affects both the code and phase measurements identically with only a sign change. The errors are typically 5 meters within one standard deviation (68.3%) although they can vary between 1 to 100 (or more) meters. The errors are especially relevant now since the sun is at the peak of its 11-year solar cycle. In a test conducted during relatively low ionospheric activity in September 1998, the differential ionospheric error standard deviation grew from 3.6 cm for a 67 km baseline to 21.9 cm for a 461 km baseline, showing how ionospheric error decorrelates as baseline distance increases [2].

2.2.1.2. *Tropospheric Delay*

Tropospheric delay is broken into dry and wet components. The dry component accounts for approximately 80-90% of the delay, but it can be accurately predicted to within 1% accuracy at zenith. The wet component accounts for the remaining 10-20% and is a function of water vapor in the local area. The error caused by the wet component can only be predicted to within 20% accuracy [12]. Local temperature, barometric pressure, and relative humidity play roles in the magnitude of this component. The dry component delay is typically around 2 meters of error and the wet component adds an additional 1-80 cm of error [11]. Tropospheric errors are usually modeled effectively, so the only concern is the unmodeled differential tropospheric errors. Residual (unmodeled) differential tropospheric errors typically do not exceed 3 cm for baselines under 500 km [12].

2.2.1.3. *Ephemeris Prediction Error*

Each individual satellite has ephemeris parameters optimally estimated and uploaded by the GPS ground segment. These parameters are used to calculate satellite position over time. A residual error is present within each estimate. This error, projected onto the line-of-sight between the user and the satellite, is approximately 4 meters (1σ) for both phase and code measurements [1]. Using precise ephemeris eliminates all but a few centimeters of this error.

2.2.1.4. *Measurement Noise*

Measurement noise is any noise generated within a receiver while taking measurements. Some of the noises come from thermal effects, oscillator stability, and

jitter in the receiver tracking loops. The magnitude of the noise is dependent upon the receiver design, making it different for each receiver. There is wide difference between the amount of noise on code and phase measurements. Code measurement noise can be in meters of error while phase measurement noise is only in millimeters [11]. Measurement noise is not correlated between receivers regardless of the type of measurement. DGPS techniques will therefore amplify measurement noise, but normally the noise can be easily removed with filtering before applying the technique.

2.2.1.5. Multipath

Multipath is caused by a signal arriving at a receiver by multiple paths and is a function of receiver location and surrounding environment. One signal path is the direct path for between the satellite and the receiver antenna, but the others are due to reflections off nearby objects such as buildings. These signal reflections degrade both code and phase measurements and affect both standard and differential GPS accuracy. Typical of multipath error magnitudes are around 1-2 cm (1σ) for phase measurements and 2 meters (1σ) for code measurements. Multipath is highly localized and is uncorrelated between receivers unless they are virtually right next to each other. DGPS techniques therefore amplify multipath error over longer baselines.

2.2.1.6. Clock Errors

The atomic satellite clocks are extremely stable, but may vary up to one millisecond from GPS system time. This small offset in time translates to 300 km in pseudorange error. The nominal error after the broadcast corrections have been applied is 3 meters (1σ) for both phase and code measurements [1]. The clock correction terms are clock

bias (a_{f0}), clock drift (a_{f1}), and frequency drift (a_{f2}) and are combined into a 2nd order polynomial (Equation (2-1)):

$$\delta t = a_{f0} + a_{f1}(t - t_{oc}) + a_{f2}(t - t_{oc})^2 + \Delta t_r \qquad \textbf{(2-1)}$$

The Δt_r term accounts for a relativistic periodic effect caused by a slight eccentricity in a satellite orbit. These "fitted" estimates are transmitted by the Master Control Station (MCS) in the navigation message. These errors are common for all measurements collected at a common time, so they are completely removed using DGPS techniques.

2.2.1.7. Satellite Availability (SA)

The single largest GPS error source is the SA. The Department of Defense (DOD) intentionally adds errors for the GPS SPS to degrade the navigation solution. SA is implemented by dithering the satellite clock and intentionally inducing errors into the broadcast ephemeris data. The total error estimated for an error budget is typically 32.3 meters (1σ) [1]. As mentioned earlier, SA should be removed from the SPS by 2006. SA is generated in each satellite and is uncorrelated between satellites. If both the reference and mobile receiver view the same set of satellites, SA is completely correlated due to clock dithering and is removed using DGPS techniques. This complete cancellation is true only if the clock dither portion of SA is utilized (which is normally the case) [12].

2.3. Code-based DGPS

There are two primary categories in applying "standard" DGPS -- code-based techniques and carrier-based techniques. Code-based DGPS techniques use GPS pseudorange measurements to calculate the coordinate location of the reference receiver. One implementation of this involves differencing in the position domain. Using this

technique, the actual set of coordinates is assumed to be known perfectly, and the GPS-determined position is differenced with the actual position to calculate the bias in the pseudorange measurements. This coordinate difference bias can then be applied to a remote receiver for both static and kinematic baselines. This is mathematically equivalent to single differencing. In practice, the only limitation to this method is that both receivers must be using the same set of satellites. However, this one limitation has proven to be severe, so the position domain approach is not often used in practice.

There is a variation of this technique used more commonly that does not require the same set of satellites to be used. Instead of determining the coordinate difference, a pseudorange correction value is calculated for every satellite using the reference receiver. The reference receiver station then sends the pseudorange correction values to the remote receivers, which choose the satellites they need based on the set of satellites visible to them. Errors in position are typically around 1-2 meters for baselines up to 30 km [13].

2.4. Carrier-based DGPS

Carrier-based DGPS techniques are more precise than code-based techniques. Instead of using GPS pseudorange measurements, the number of carrier-phase cycles between a satellite and a receiver are counted. This measurement is calculated by integrating the L1 or L2 carrier Doppler frequency offset over the interval of the time epoch. When using code-based techniques, the pseudorandom code is used for timing purposes since it is generated in a known sequence. There is no such sequence when dealing with the carrier-phase cycles.

To determine the measurement, a double-difference process is required. Single differences are calculated between two satellites (x,y) for each of a and b receivers. This is done for both phase (Equation (2-2)) and range measurements (Equation (2-3)):

$$\Delta\nabla\phi_{ab}^{xy} = \phi_a^x - \phi_a^y - \left(\phi_b^x - \phi_b^y\right) \tag{2-2}$$

$$\Delta\nabla R_{ab}^{xy} = R_a^x - R_a^y - \left(R_b^x - R_b^y\right) \tag{2-3}$$

These values are then differenced with each other to obtain the measurement-minus-range (MMR) double-difference value (signified with an overscore ($\bar{\phi}$)):

$$\begin{aligned}\Delta\nabla\bar{\phi}_{ab}^{xy} &= \Delta\nabla\phi_{ab}^{xy} - \Delta\nabla R_{ab}^{xy} \\ &= \Delta\nabla N_{ab}^{xy} + \textit{differential errors}\end{aligned} \tag{2-4}$$

The MMR double difference value equals the double-difference value of the carrier-phase integer ambiguities between each satellite and receiver combination ($\Delta\nabla N_{ab}^{xy}$), plus the sum of the differential errors. The $\Delta\nabla N_{ab}^{xy}$ values are always fixed integers and must be determined to achieve true centimeter level accuracy. An advantage to military users is full access the encrypted P-code, usually referred to as the Y-code. Commercial users have to rely on sophisticated receivers that use a correlation technique to recover the full carrier-phase and pseudorange for the P(Y)-code measurements.

2.5. NetAdjust [2]

The most important contribution of a receiver network is not the improved precision, but the improvement in reliability and availability of a fixed integer solution for carrier-phase ambiguity resolution. Networks of reference receivers are more robust against outliers in data than a single-reference solution. A network can also increase the probability of successfully determining ambiguities by reducing the differential GPS

errors. NetAdjust uses a network of reference receivers to increase the distance significantly over which single-frequency carrier-phase ambiguity resolution can be performed. This is done without sacrificing accuracy or increasing the time to resolve the ambiguities.

2.5.1. Differential Measurement Errors

Carrier-phase ambiguity resolution is limited by measurement errors that are not removed in the double-differencing process. These measurement errors can be grouped into spatially correlated errors (atmospheric and satellite position errors) and uncorrelated errors (receiver noise and multipath). The dominant differential measurement errors for phase measurements are distance dependent. These spatially correlated errors cause the differential measurement errors to grow as baseline length increases, which in turn decreases the ability to perform carrier-phase ambiguity resolution successfully. The NetAdjust algorithm explicitly attempts to minimize the sum of the differential error variances. This is accomplished using a measurement covariance matrix that represents the spatial relationships between the various DGPS error sources. NetAdjust separates the error sources into four separate terms: clock errors, correlated errors, uncorrelated errors, and the integer ambiguity. Equation (2-5) is the MMR observable of a phase measurement. The MMR observable is the geometric range between the user and the satellite subtracted from the raw measurement. As such, it includes all the errors in the measurement, but not the actual range to a satellite:

$$\bar{\phi} = \delta\phi_{clock} + \delta_c\phi(p_{rec}) + \delta_u\phi + N \qquad \textbf{(2-5)}$$

The $\delta\phi_{clock}$ term includes clock errors that will be completely cancelled by the double-differencing process. The $\delta_c\phi(\boldsymbol{p}_{rec})$ term is the correlated error term and

includes all spatially correlated errors, which are a function of the receiver position ($\boldsymbol{p}_{rec}$). The $\delta_u\phi$ term is the uncorrelated error term. It includes all other errors that are not a function of the receiver position (multipath and noise). The final term is the integer ambiguity (N), which is a vector. This is the key term to resolve in order to use carrier-phase DGPS techniques successfully.

2.5.2. Zero-point

The zero-point ($\boldsymbol{p}_0$) is a fixed position in the middle of the established receiver network. All differential errors will be referenced from this point, although results are not necessarily sensitive to its location. The relative differential error term then becomes:

$$d_c\phi(\boldsymbol{p}_{rec}, \boldsymbol{p}_0) = \delta_c\phi(\boldsymbol{p}_{rec}) - \delta_c\phi(\boldsymbol{p}_0) \qquad \textbf{(2-6)}$$

As stated earlier, the goal is to separate errors not cancelled by double differencing from those that are cancelled. Combining Equations (2-5) and (2-6) together and forming a double-difference measurement between any two receivers and two satellites creates Equation (2-7):

$$\Delta\nabla\overline{\phi} = \Delta\nabla d_c\phi(\boldsymbol{p}_{rec}, \boldsymbol{p}_0) + \Delta\nabla\delta_u\phi + \Delta\nabla N \qquad \textbf{(2-7)}$$

Two terms drop out since they equal zero. The $\Delta\nabla\delta\phi_{clock}$ term disappears since the clock terms cancel out, and the $\Delta\nabla\delta_c\phi(\boldsymbol{p}_0)$ term falls away in the double-differencing process. For this thesis case, the first two terms on the right side of Equation (2-7) are estimated and the integer ambiguity is assumed known. If the terms are estimated perfectly, the double-difference measurement-minus-range values are equal to zero.

Figure 2-1 shows an example output of double-difference measurement-minus-range residual values after correcting for the integer ambiguities. The L1 and L2 output are

both within ±1.5 cycles. The widelane (Lw) output is much lower at around ±0.3 cycles. The residual error shown in Figure 2-1 is the magnitude of the correlated error that has not been determined.

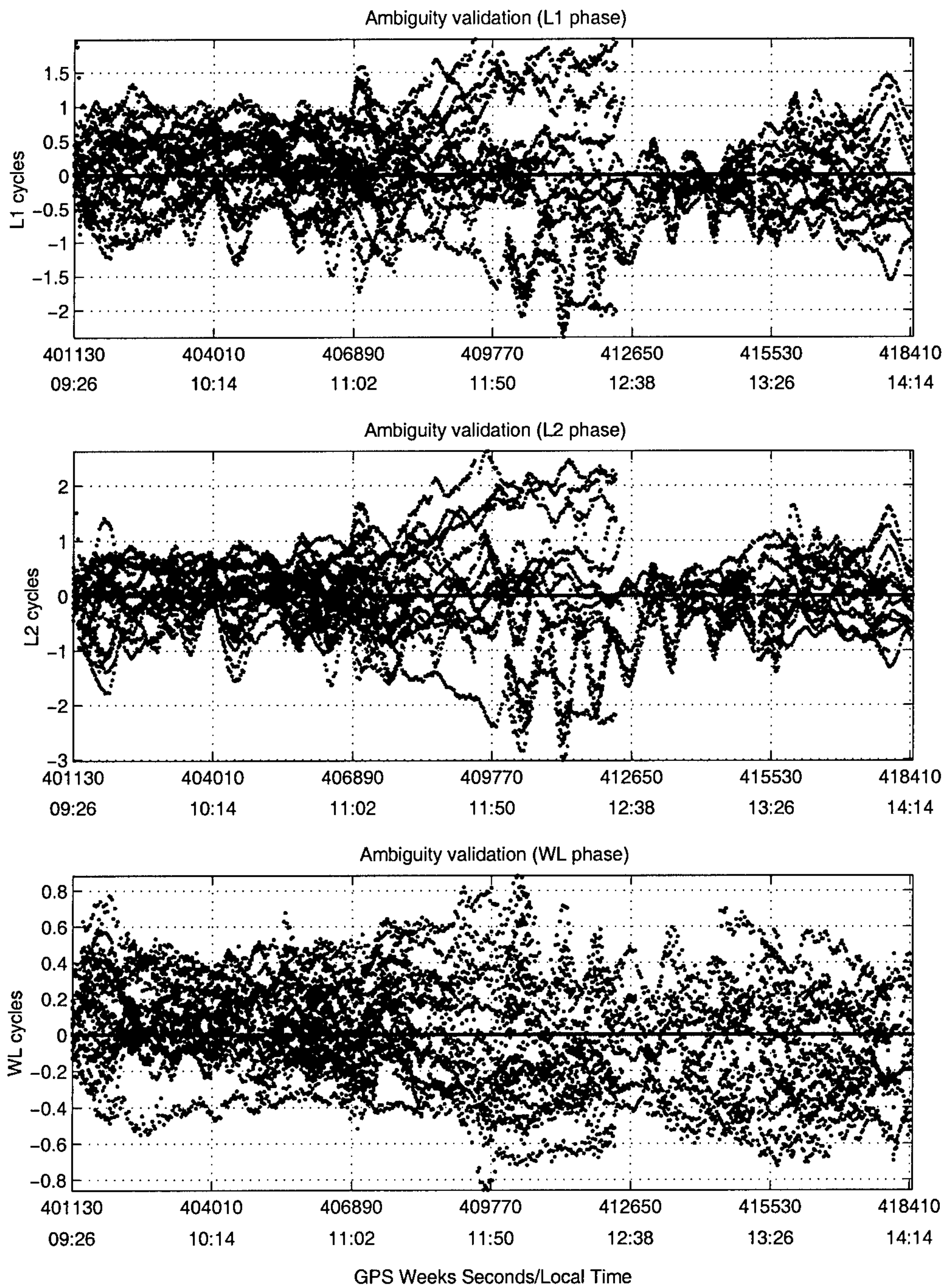

Figure 2-1. Double-difference residual values for 49.8 km baseline

2.5.3. *Computation Point*

An important distinction to make with NetAdjust is that it corrects the reference receiver measurements, as opposed to providing differential range corrections to be applied to the mobile receiver's measurements. The goal of NetAdjust is to determine a set of corrections which will minimize the error variance of the double-difference measurement errors between the corrected reference receiver measurements and measurements obtained from a mobile receiver located at a "computation point". A computation point is specified as the approximate location of the mobile receiver. It is for this point that differential errors are estimated.

All measurements are split into two separate vectors, one for the network ($\mathbf{l}_n$) and one for the computation point ($\mathbf{l}_{cp}$). The $\mathbf{l}_n$ vector contains all of the measurements available from the reference receiver network. The $\mathbf{l}_{cp}$ vector contains the remote receiver measurements. These remote receiver measurements are considered unavailable for NetAdjust computations. Thus, they are available for the mobile user, but not for network estimation.

Figure 2-2 shows the interrelationships between the various measurement and correction variables. All operations within the box are executed by the NetAdjust method, while the mobile receiver at the computation point executes operations outside the box. For a more in-depth description, refer to [2].

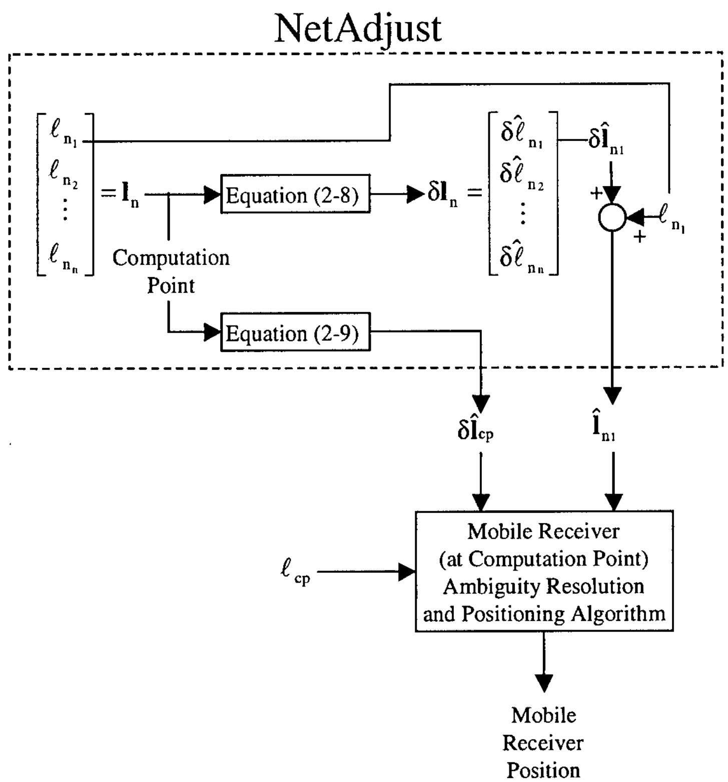

Figure 2-2. NetAdjust algorithm flowchart

The final form of the NetAdjust method is given in Equations (2-8) and (2-9):

$$\delta\hat{\mathbf{l}}_{\mathrm{n}} = C_{\delta\ell_{\mathrm{n}}} B_{\mathrm{n}}^{\mathrm{T}} \left(B_{\mathrm{n}} C_{\delta\ell_{\mathrm{n}}} B_{\mathrm{n}}^{\mathrm{T}}\right)^{-1} \left(B_{\mathrm{n}} \ell_{\mathrm{n}} - \Delta\nabla N_{\mathrm{n}}\right) \tag{2-8}$$

$$\delta\hat{\mathbf{l}}_{\mathrm{cp}} = C_{\delta\ell_{\mathrm{cp}},\delta\ell_{\mathrm{n}}} B_{\mathrm{n}}^{\mathrm{T}} \left(B_{\mathrm{n}} C_{\delta\ell_{\mathrm{n}}} B_{\mathrm{n}}^{\mathrm{T}}\right)^{-1} \left(B_{\mathrm{n}} \ell_{\mathrm{n}} - \Delta\nabla N_{\mathrm{n}}\right) \tag{2-9}$$

The $\delta\hat{\mathbf{l}}_{\mathrm{cp}}$ vector represents the corrections to be applied to the measurements collected by the mobile receiver at the computation point (ℓ_{cp}). The $\delta\hat{\mathbf{l}}_{\mathrm{n}}$ vector represents the corrected measurements from a single reference receiver. $\mathbf{B}_{\mathrm{n}}$ is the double difference matrix formed based upon available $\mathbf{l}_{\mathrm{n}}$ measurements. Multiplying the measurement vector $\mathbf{l}_{\mathrm{n}}$ by $\mathbf{B}_{\mathrm{n}}$ generates all possible linearly independent double difference combinations of $\mathbf{l}_{\mathrm{n}}$. The $\mathbf{C}_{\delta\ell n}$ and $\mathbf{C}_{\delta\ell cp,\delta\ell n}$ terms are part of the larger $\mathbf{C}_{\delta\ell}$ covariance

matrix which describes the second moments of the differential GPS errors. This covariance matrix represents the correlations between all of the measurements in the network. The **N** term represents the vector of integer ambiguities.

Only one set of reference receiver measurements is required due to the data encapsulation effect of NetAdjust. The encapsulation effect occurs since the corrected measurements in $\mathbf{l}_n$ contain the minimal differential error variances calculated from the entire reference receiver network. Standard differential positioning or ambiguity resolution can then be performed between a mobile receiver and one of the adjusted reference receivers.

After the network adjustment is completed, the corrected measurements are more accurate than the original raw measurements. The improvement gained from NetAdjust grows as the baseline length increases. Over short baselines, the correlated errors are very small, and NetAdjust has little effect, since other receivers in the network will contribute very little new information. As the baseline length increases, correlated errors begin to dominate, and the other reference receivers are able to contribute to the error reduction [3].

2.6. Virtual Reference Receiver Concept

As baseline lengths increase, the algorithms used by many software packages tend to break down. In order to work around this deficiency, the baseline length needs to be reduced. One way of shortening a baseline is to create a virtual reference receiver at a set of coordinates that is much closer to the mobile receiver than the reference receiver. To work, a virtual reference receiver must successfully provide all the measurements that an actual reference receiver would at the same location.

An initial assumption must be made that all GPS data processing algorithms use a measurement-minus-range observable value, either explicitly or implicitly. NetAdjust changes the measurements so that the MMR value of the corrected measurement will yield minimized differential errors. The MMR value of the corrected measurements at the one reference receiver is described by

$$\hat{\bar{\phi}}_{ref} = \hat{\phi}_{ref} - r_{ref}^{sv} \tag{2-10}$$

The term on the left-hand side, $\hat{\bar{\phi}}_{ref}$, is the corrected MMR value from the reference receiver. The first term on the right-hand side, $\hat{\phi}_{ref}$, is the NetAdjust-corrected phase measurement from the reference receiver. The second term on the right, r_{ref}^{sv}, is the range between the reference receiver and the satellite.

The goal is to generate a NetAdjust-corrected phase measurement for a virtual receiver representative of the corrected measurements that would be valid for a receiver at an arbitrary location. In order to maintain the minimized differential errors, the MMR value calculated using the NetAdjust-corrected phase measurement should be the same as the MMR value of the original measurements at the reference receiver location. Expressed mathematically:

$$\begin{aligned}
\hat{\bar{\phi}}_{vir} &= \hat{\bar{\phi}}_{ref} \\
\hat{\phi}_{vir} - r_{vir}^{sv} &= \hat{\phi}_{ref} - r_{ref}^{sv} \\
\hat{\phi}_{vir} &= \hat{\phi}_{ref} + r_{vir}^{sv} - r_{ref}^{sv} \\
\hat{\phi}_{vir} &= \hat{\phi}_{ref} + \Delta r \qquad \text{(2-11)}
\end{aligned}$$

The Δr term represents the correction to be applied to move a measurement from the original reference receiver location to the new virtual receiver location. If a measurement

is missing from a reference receiver, it can be taken from another reference receiver in order to obtain a more complete set of the virtual receiver measurements.

2.7. Ashtech Office Suite (AOS)

The Ashtech Office Suite v2.0 [8] is a commercially available software package typically used for surveying applications. Its main purpose is to accomplish differential positioning. For use in this thesis, its main purpose is to process GPS data files recorded by Ashtech Z-Surveyor GPS receivers and obtain the carrier-phase integer ambiguities for the receiver network baselines. The GPS data files will be referred to as B files and E files in this thesis to establish a connection to the naming convention used by the Ashtech receivers and software package. Each file is named for the first letter in the file [9]. The B file contains all the raw GPS measurement data in binary format. The E file contains the satellite broadcast ephemeris data in binary format. AOS is also used to determine the percentage of phase positions correctly resolved for the kinematic baselines of interest. All reports generated by the software package are saved in hypertext markup language (HTML) format.

In order to process B and E files, a hardware dongle driver must be present in the parallel port of the personal computer being used to process the files. The dongle is a hardware key that contains the software license information necessary to process B and E files. It is transportable to any other personal computer with AOS v2.0 and the license information installed to activate the dongle. Any attempt to process files without the dongle present will cause the software to cease functioning until it is put in the parallel port.

AOS is capable of handling both static and kinematic baselines and will automatically recognize the type of file imported. If it incorrectly interprets the file type, it is possible to change the file manually to the correct type. Once all the desired files have been imported for the receiver network, AOS offers a variety of methods with which to process the data. The automatic selection will recognize the type of file and length of baseline and select the default processing option. For instance, if a kinematic baseline less than 30 km were selected, the automatic selection would process that baseline using on-the-fly (OTF) algorithms. Other processing algorithm options available include Stop&Go and DGPS. A host of utilities and reports are available to assist in the processing and evaluation of data. In addition, there are a number of manually selectable processing options that can remove faulty data, display cycle slips, or shorten the amount of data to process.

Any processing errors or file anomalies can be viewed in the processing window. Errors are highlighted in red for easy identification. A log file can be generated if desired to record all actions AOS performs while processing a receiver network. Each baseline is color-coded to identify which baselines have been processed and if the respective ambiguities have been successfully resolved or not.

2.8. MATLAB®

MATLAB® v5.3 [10] was used to program two files important to the thesis. MATLAB® is a high-performance language used for technical computing and data display. It integrates programming, graphical figures, and computation into a useful environment for a variety of engineering applications. In this thesis, its capability for reading and extracting information from text files and then creating and formatting text

output files has been utilized. Its graphical capabilities are extensively used as well to express a number of key concepts throughout the thesis.

2.9. Summary

This chapter introduced standard DGPS techniques and sources of GPS errors. The background required to understand the key concepts used in Chapters 3 and 4, such as the NetAdjust algorithm and software tools like AOS, were reviewed.

3. Methodology

3.1. Overview

This chapter describes the procedure used to produce NetAdjust-corrected measurement files and virtual receiver measurement files. Selected AOS options, alternatives, and reasoning used to process the B and E files are discussed in detail. Generation of report formats, MATLAB® code, and the NetAdjust executable files are also described to give a complete picture of the entire process.

3.2. Data Collection

On 10 October 1999 four Ashtech receivers were stationed across WSMR at locations that surrounded the typical flight path of a 746th TS GPS test mission. These four receivers were all placed in locations frequently used as references sites for 746th TS test missions and they are all viable locations for a reference receiver to be permanently fixed. A fifth receiver is permanently fixed at CIGTF with known ECEF coordinates. The remote receiver was mounted in a 746th TS vehicle. Figure 3-1 shows the relative locations of the five reference receivers to each other in the test receiver network.

Data was recorded at one-second intervals for a seven-hour period at the known fixed site (CIGT). Data recorded by the other five receivers is within a subset of this seven-hour period. All data was recorded in the Ashtech B and E file formats. Figure 3-2 shows the time intervals that data was recorded for each receiver. Note that all receivers were recording simultaneously for almost four hours between 15:30 and 19:30 GMT.

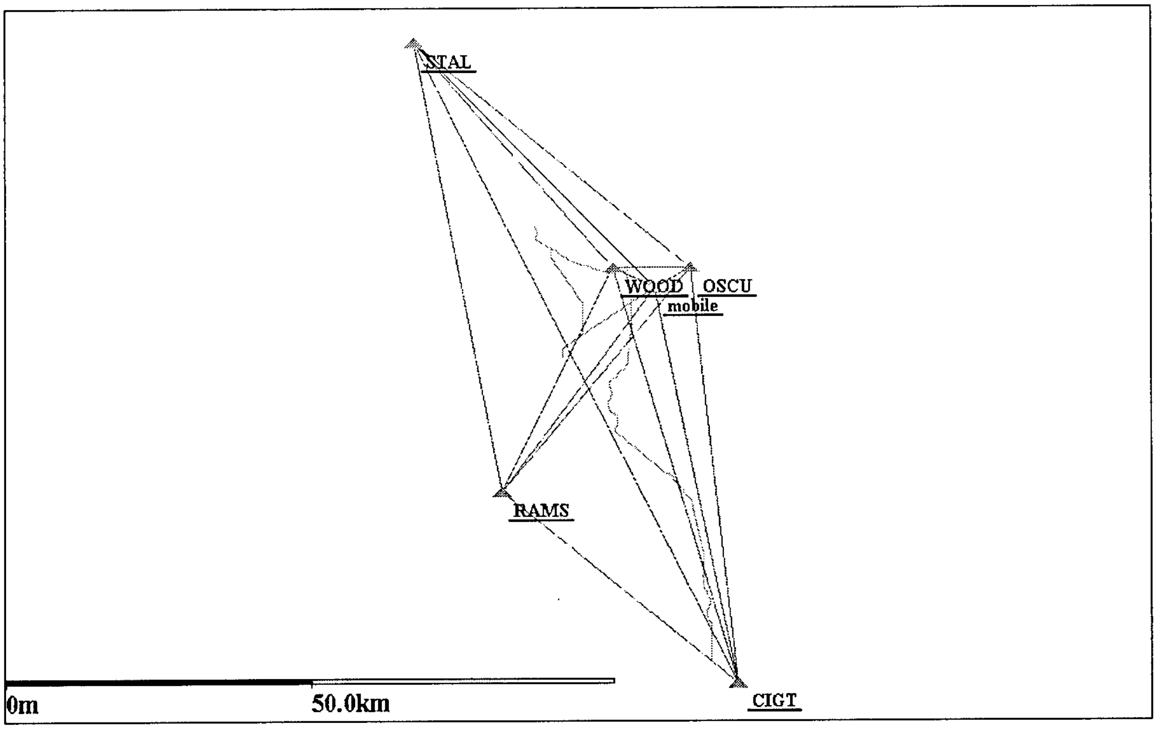

Figure 3-1. Reference receiver locations for test receiver network on map of White Sands Missile Range.

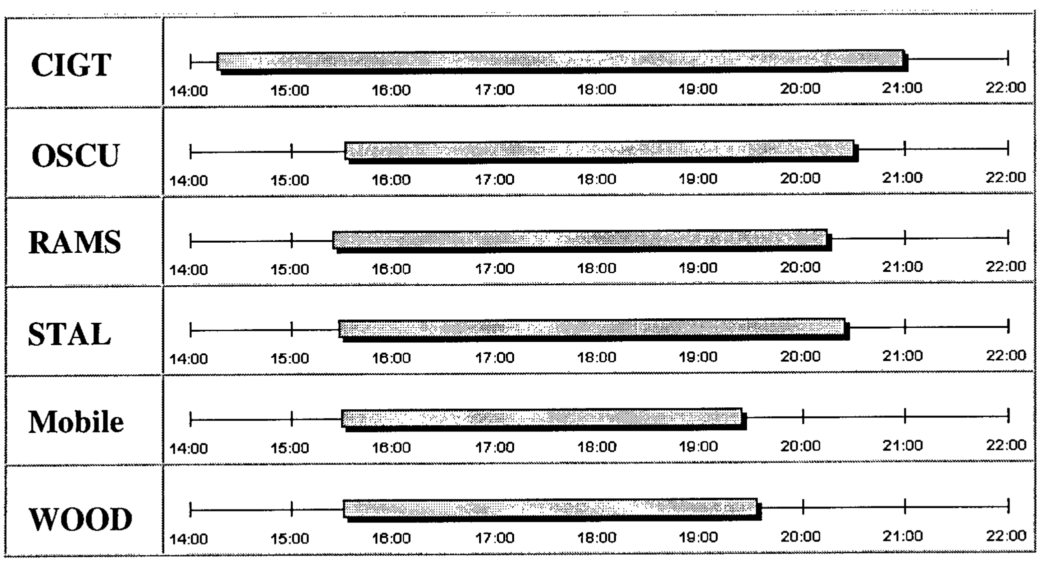

Figure 3-2. Ground test data collection time periods for the five reference receiver sites and one mobile receiver (Times are UTC – for local times, subtract 6 hours).

3.3. *AOS Processing*

AOS requires some initial setup before any processing can begin. An ellipsoid model and datum line must be selected and the type of frequency measurements to use must be specified. To obtain the values of interest in this thesis, the WGS-84 ellipsoid model and datum were selected. The widelane frequency selection was changed from 30 km to 120 km to allow AOS to attempt L1 ambiguity resolution for the longest baseline in Figure 3-1 (STAL-CIGT, 116km).

3.3.1. *Initial Processing*

All the desired static and kinematic receiver files were individually selected and inserted into AOS for processing. The initial processing occurred automatically after inserting the files, as AOS converts the B files into observable (.obs) files and the E files into RINEX format broadcast ephemeris (.99n) files [14]. AOS also created a broadcast ephemeris file in the binary EF-18 format [15]. If desired, precise ephemeris may be downloaded from various web sites in SP3 format [15].

Once all the files were added to the project, the observable files were checked to ensure that AOS correctly flagged the files as static or kinematic. If a static file was incorrectly flagged as kinematic or vice versa, the file properties were manually corrected. AOS automatically establishes all baselines between all static points and between static points and kinematic trajectories. The last step before instructing AOS to process the project was to assign coordinates manually for the fixed known site (CIGT). After processing all the baselines, a fixed network adjustment was run to obtain the most accurate coordinates for each of the unfixed reference receiver points. These coordinates were used as the fixed reference receiver locations for future processing.

To get a feel for the accuracy of the reference receiver coordinates, the three-dimensional baseline vectors between the final receiver coordinates were calculated. These results were then differenced with the given AOS values for the baseline x, y, and z components, based upon the GPS measurements. The resulting differences are called the misclosures. The misclosures between CIGT and each of the other reference receivers are italicized in Table 3-1.

Table 3-1: Summary of reference receiver ECEF coordinates misclosures (meters)

		OSCU	CIGT	WOOD	RAMS
X	STAL	-0.059	*-0.053*	0.040	0.026
Y		0.034	*0.155*	-0.083	0.104
Z		-0.010	*0.030*	-0.048	0.053
X	OSCU	---	*0.035*	-0.006	-0.004
Y		---	*0.087*	0.008	-0.016
Z		---	*0.000*	0.007	-0.005
X	CIGT	---	---	*0.036*	*-0.014*
Y		---	---	*-0.084*	*0.156*
Z		---	---	*-0.056*	*0.046*
X	WOOD	---	---	---	0.002
Y		---	---	---	-0.027
Z		---	---	---	-0.014

The coordinates used for CIGT are the results of a site survey, and they are assumed to be known perfectly. All of the other receiver error coordinates were calculated relative to the CIGT site. The receivers with the longer baselines (STAL and RAMS) have greater errors than those with smaller baselines (OSCU and WOOD). A sensitivity analysis of the results to receiver coordinate accuracy was not performed. The results can only improve in a receiver network where all the receivers have perfectly known

coordinates obtained via a site survey or calculated over days of continuous observation. A full sensitivity analysis is recommended for follow-on research.

3.3.2. Integer Ambiguity File Creation

When processing, AOS sought to solve each individual baseline between static receivers independently. Upon process completion and after the fixed network adjustment was accomplished, report files for each of the ten static baselines and five kinematic baselines were saved. There was a variety of options for what the baseline report file would display. The essential data inside the report are the identification of a reference satellite, the available satellites (and their associated availability start and stop times), the L1 and L2 cycle slip summary, and the integer ambiguities determined by the program. In the report options settings, three selections were removed from the report output -- "detailed point information", "all solutions", and "ambiguity resolution". The table of contents was removed to simplify the ambiguity extraction process. Each file was saved with a nine-character name related to the baseline for ease of recognition through the rest of the procedure (eg: CIGT-OSCU.htm). As discussed earlier, AOS only allowed report files to be saved in HTML format. Microsoft Word [16] was used to convert the report files to text format.

Once the static baseline reports were saved in text format, a custom-generated MATLAB® [10] script file was used to determine, extract, and format the integer ambiguities from the saved text report files. The report files had to be in a standard text format in order for the script file to execute correctly. The MATLAB® script created three files for each baseline - one for each type of integer ambiguity (L1, L2, &

widelane). AOS was not always able to determine the integer ambiguities for all three wavelengths, especially for the longer baselines.

A separate routine was run to attempt to fill any integer ambiguity holes left by AOS. All the original B files, the ambiguity files extracted via the MATLAB® script file, reference receiver positions, and ephemeris information were fed into a custom designed DOS executable file called NetAmb. The executable routine attempted to resolve any missing integer ambiguities using ambiguity combinations from the entire network, and then output a new integer ambiguity file. NetAmb was run separately for each frequency.

3.3.3. NetAdjust B File Creation

Once the complete set of ambiguities for every baseline combination was calculated, the setup to run NetAdjust began. NetAdjust required the original B files, a database of site coordinates, the ephemeris file, and the ambiguity files. It also required a pre-specified covariance parameter file that described the spatial correlation of the errors. The covariance parameters used for this test were the same as those used in [2]. Finally, a mobile receiver trajectory file containing the computation points to be used by NetAdjust was included. This file was exported from the AOS-generated mobile receiver observable file in an ECEF coordinate frame format. NetAdjust then applied the corrections to the measurements collected by the receiver at the computation point and combined the result with the corrected reference receiver measurements as shown in Figure 2-2. The outputs from NetAdjust are new B files for every receiver that include corrected measurements.

3.3.4. Virtual B File Creation

After the NetAdjust B files were created for every static receiver in a network, the virtual receiver B file creation was performed. The virtual reference receiver may be located at any point, although ideally it is placed in a location conducive to shortening baseline length.

The virtual receiver software routine sorted through the NetAdjust B files in a specified order to extract the corrected measurements. It used all of the valid corrected measurements from the first reference receiver, translating them to the specified virtual reference receiver location using the procedure specified in Section 2.6. If any measurements were missing from the first reference receiver, it would then look for them in the second reference receiver, translating them to the same virtual receiver location. This procedure was repeated through all of the reference receiver files.

3.3.5. Final processing

The location of the virtual reference receiver was chosen to be centered within the mobile receiver trajectory (see Figure 3-3). This location was ideal to minimize the baseline length between the virtual reference receiver and the mobile receiver for the greatest number of points. The time span of the trajectory that surrounds the virtual reference receiver location was 3 hours. After the NetAdjust and virtual B files were created, each of the 3-hour B files was split into smaller time increments to speed processing. For example, in one case the B file was split into nine 20-minute files. This was done to all of the original (raw) B files as well the NetAdjust-corrected and virtual receiver B files. Start and stop times for each of the 9 20-minute time increments are shown in Table 3-2.

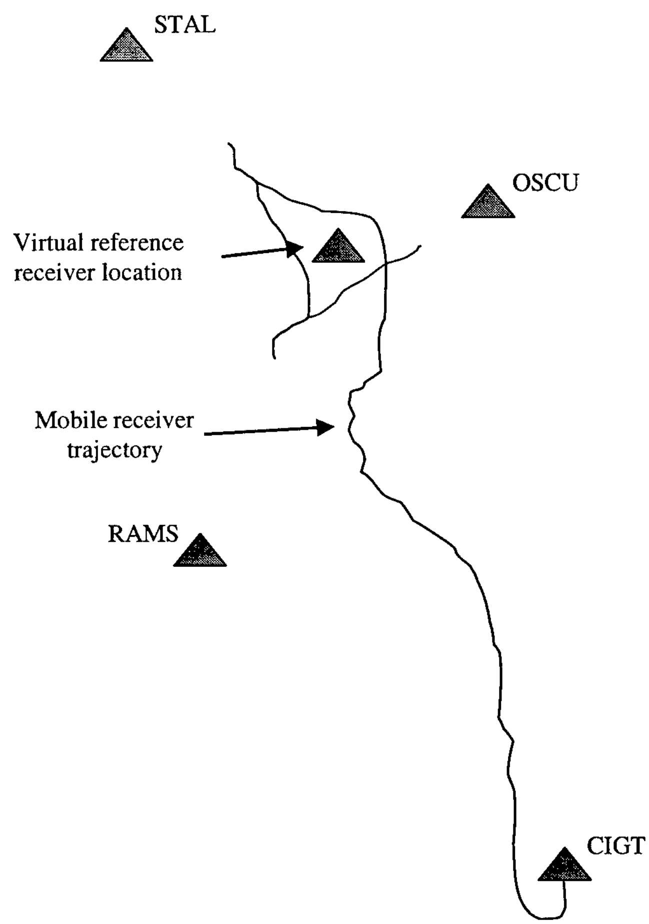

Figure 3-3. Location of coordinates used for virtual reference receiver calculations. Note that location was centered within the mobile receiver trajectory.

Table 3-2: Test period start and stop times for 20-minute periods in GPS week-seconds and Greenwich Mean Time (GMT)

	Start Time	Stop Time
Increment 1:	403700 (16:08:20)	404899 (16:28:19)
Increment 2:	404900 (16:28:20)	406099 (16:48:19)
Increment 3:	406100 (16:48:20)	407299 (17:08:19)
Increment 4:	407300 (17:08:20)	408499 (17:28:19)
Increment 5:	408500 (17:28:20)	409699 (17:48:19)
Increment 6:	409700 (17:48:20)	410899 (18:08:19)
Increment 7:	410900 (18:08:20)	412099 (18:28:19)
Increment 8:	412100 (18:28:20)	413299 (18:48:19)
Increment 9:	413300 (18:48:20)	414499 (19:08:19)

Processing runs were accomplished for the total 3-hour period, four 2-hour periods, seven 1-hour periods, and nine runs for 20-minute, 10-minute, 5-minute, and 2-minute periods. Table 3-2 shows an example for one baseline.

Table 3-3: Data point percentages for 4-receiver NetAdjust CIGT baseline case

Increment #:	1	2	3	4	5	6	7	8	9	Avg %
Full	99.6									**99.60**
3 hours	100									**100.00**
2 hours	95.6	100	100	100						**98.90**
1 hour	100	100	100	91.1	100	75.3	100			**95.20**
20 minutes	100	100	0	0	100	0	100	75.7	100	**63.97**
10 minutes	0	100	0	0	0	0	0	0	100	**22.22**
5 minutes	100	100	0	0	0	0	0	0	100	**33.33**
2 minutes	0	100	0	0	0	0	0	0	100	**22.22**

This methodology was applied to maintain consistency when comparing results from simulations of different network setups. For each case, the first run began at the Increment 1 start time and concluded the appropriate time later. The second run began with the Increment 2 start time. This process was repeated through all of the time increments. Table 3-4 shows the start and stop times for each of the possible cases.

Table 3-4: Start and Stop times for the increments within each time interval

Increment #:	1	2	3	4	5	6	7	8	9
3 hours									
Start time:	403700								
Stop time:	414499								
2 hours									
Start time:	403700	404900	406100	407300					
Stop time:	410899	412099	413299	414499					
1 hour									
Start time:	403700	404900	406100	407300	408500	409700	410900		
Stop time:	407299	408499	409699	410899	412099	413299	414499		
20 minutes									
Start time:	403700	404900	406100	407300	408500	409700	410900	412100	413300
Stop time:	404899	406099	407299	408499	409699	410899	412099	413299	414499

At the end of each processing run, the percentage of phase positions resolved was recorded. The percentage of phase positions resolved equates to the percentage of time a fixed ambiguity solution was available. The results of all the runs for each period were averaged to obtain the final percentages used in Chapter 4.

3.4. Summary

The procedure used to obtain results concerning NetAdjust and virtual reference receiver performance was broken down into several steps to reduce complexity. The initial step was to process the original B files in AOS and extract the integer ambiguities for each static baseline. The next step was to use NetAmb to process all the ambiguity files in an attempt to resolve as many integer ambiguities as possible. NetAdjust was then applied to the original B files using the integer ambiguities to calculate corrected measurements. Then the virtual reference receiver software was applied to the NetAdjust B files to calculate a new B file that simulated an actual reference receiver at the specified coordinates. The original, NetAdjust, and virtual reference receiver B files were then split and processed in AOS to obtain the percentage of time an integer ambiguity solution was available.

4. Results

4.1. *Overview*

Results are presented for the three different sets of files. The original (raw) B files are examined first to determine which receivers are more successful at resolving ambiguities and the role that baseline length plays. The B files with the NetAdjust-corrected measurements are examined next to determine how much the corrected measurements improve the percentage of time a fixed integer ambiguity solution is available. Finally, the use of a virtual reference receiver is analyzed, using both raw and NetAdjust-corrected files.

4.2. *Raw B file results*

The total reference receiver network was processed in accordance with the procedure described in Section 3.3.5 using the raw B files. The percentage of time a fixed solution was available differed greatly between the five reference receivers. The receivers with the shortest kinematic baselines produced results superior to those with longer kinematic baselines. Table 4-1 shows the average kinematic baseline length between the reference receiver and the mobile receiver for the 3-hour time interval of primary interest.

Table 4-1: Reference receiver kinematic baseline lengths

Ref. receiver	Baseline length (km)
WOOD	6
OSCU	17
RAMS	35
STAL	51
CIGT	67

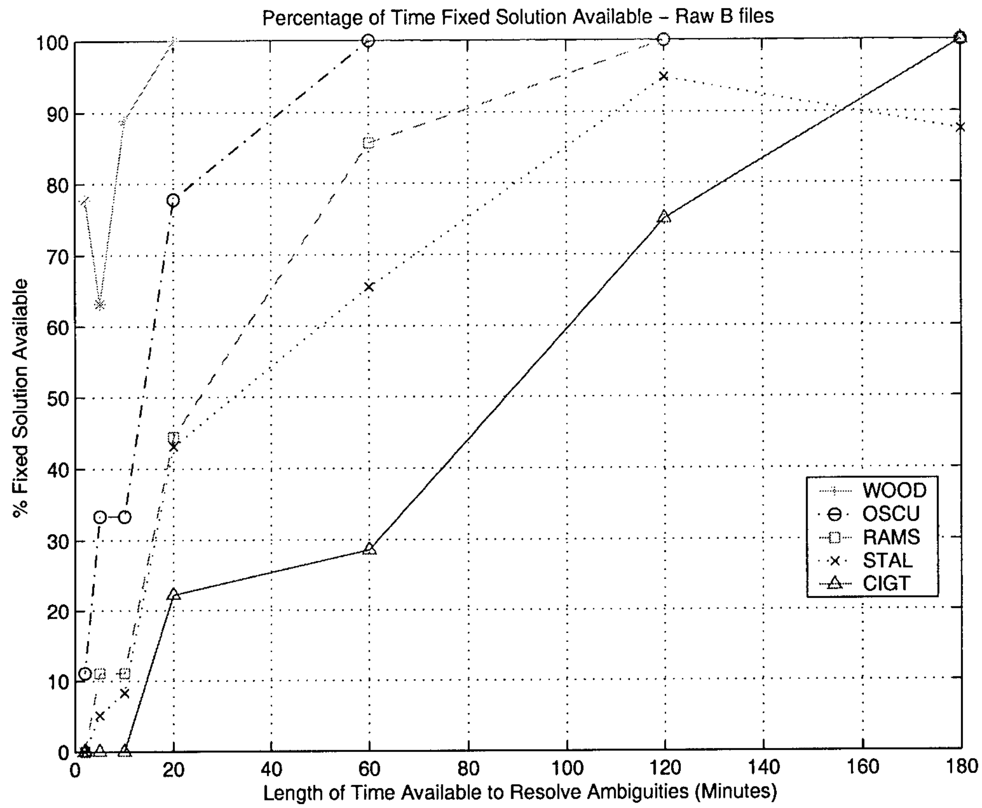

Figure 4-1. Percentage of time a fixed ambiguity solution was available in the original (raw) reference receiver B files

Figure 4-1 shows how often the fixed integer solution was available as a function of the total length of the data files, with the exception of WOOD, which was normally very close to the mobile receiver. For time periods less than 20 minutes, results were erratic for all receivers. The percentages for all the reference receivers increased in accordance with the amount of data used to resolve the ambiguities. After three hours of measurements, all the receivers reached 100% except for STAL, which actually decreased 7% from the percentage resolved over the 2-hour average time interval. This decrease is attributed to the multiple cycle slips present in the STAL measurements.

4.3. NetAdjust results

The results for the NetAdjust corrected files were then processed using several different cases. The first case includes all five reference receivers, and the results are shown in Figure 4-2. When compared to the raw B file results, little to no improvement was noted for the short baseline receivers (WOOD and OSCU). This is consistent with previous research using the NetAdjust algorithm [2]. WOOD reaches 100% by 20 minutes in both cases and OSCU reaches 80% within 20 minutes and 100% after 1-hour.

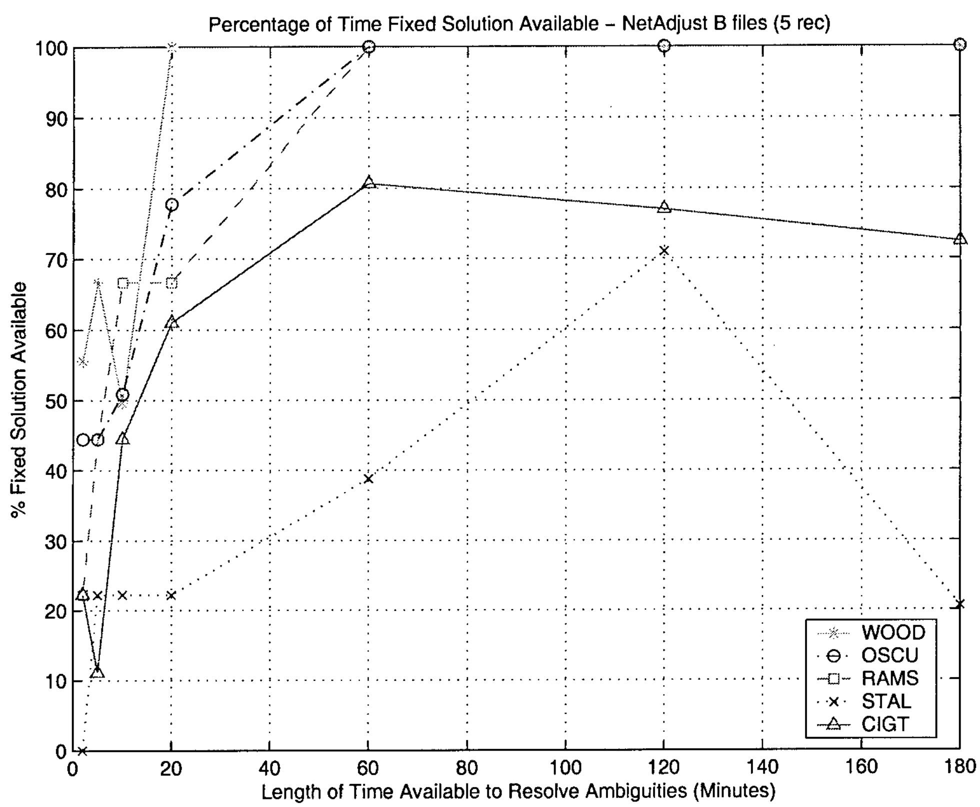

Figure 4-2. Percentage of time a fixed ambiguity solution was available in the NetAdjust corrected B files using the entire reference receiver network

Results are even more inconsistent for time periods of less than 20 minutes when using the NetAdjust-corrected measurements. It is not until 20 minutes of measurements were used that a consistent trend emerged. The results improved for this case over the

raw files for the three shortest baselines. The CIGT receiver also improved compared to the raw case, but only up to the 1-hour point. A downward trend emerged from then on. The STAL receiver was extremely inconsistent compared to the other receivers and the raw case. The percentage of time did continue to increase up to the 2-hour point, but dipped severely between there and the 3-hour point. A key factor is the baseline length. STAL and CIGT are the two longest baseline receivers and all the results except for the 3-hour case are the average of several increments. The averaging effectively negates any difficulty in resolving ambiguities for a specific time increment. When taking into account the entire 3-hour time period, the difficulties will propagate through and lower the total percentage. Another hypothesis to investigate further are possible errors in the reference receiver coordinates. Since NetAdjust assumes the reference receiver coordinates given to it are perfect, any errors in the coordinates become part of the correlated error term. Therefore, when NetAdjust removes the correlated errors, it actually induces an error in the measurements. Ideally, all the receivers would have similar lines, provided the integer ambiguity set was complete and accurate, there was common satellite visibility between all receivers, and the receiver coordinates were accurate. The inconsistency in the CIGT and STAL results was investigated in subsequent case plots.

The next case excluded the WOOD receiver to see the effect of not including the reference receiver with the shortest kinematic baseline. This case was run to determine if there were any positioning problems between WOOD and the other reference receivers. Results were expected to improve if this was true. In Figure 4-3 the two shortest baselines (OSCU and RAMS) displayed expected results. Their percentages were

slightly lower than the 5-receiver case and slightly greater than the raw case. CIGT shows a dramatic improvement compared to both the raw and 5-receiver cases. STAL improves over the 5-receiver case, but its performance is still far inferior to the other receivers.

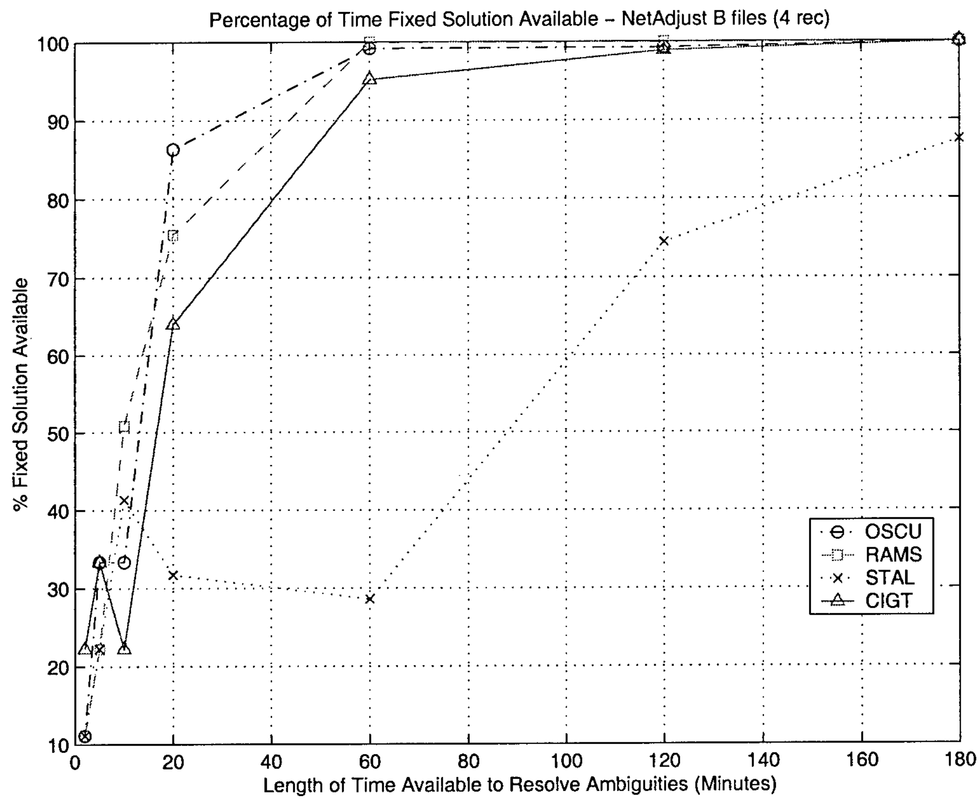

Figure 4-3. Percentage of time a fixed ambiguity solution was available in the NetAdjust corrected B files using four reference receivers

The improvement in CIGT and STAL after removing WOOD indicates a positioning problem is present within the receiver coordinates. When WOOD is removed, the errors present in the WOOD-CIGT and WOOD-STAL baseline are removed, and the NetAdjust-corrected measurements improve. The fact that STAL results are still poor indicates that there are problems present within the STAL measurements.

Since STAL displayed such consistently poor results, it was eliminated from the network. Any decline in the results indicates positioning problems between STAL and that particular reference receiver. The 3-receiver case was then processed, and the shorter baselines exhibited the expected and desired results, as shown in Figure 4-4. Both OSCU and RAMS produced results nearly identical to the 4-receiver case. However, CIGT performance dropped off significantly. This reinforces the hypothesis of errors present in the reference receiver coordinates. It also indicates that, even though the STAL measurements had problems, they still contributed measurements to the network solution that benefited CIGT in the 4-receiver case.

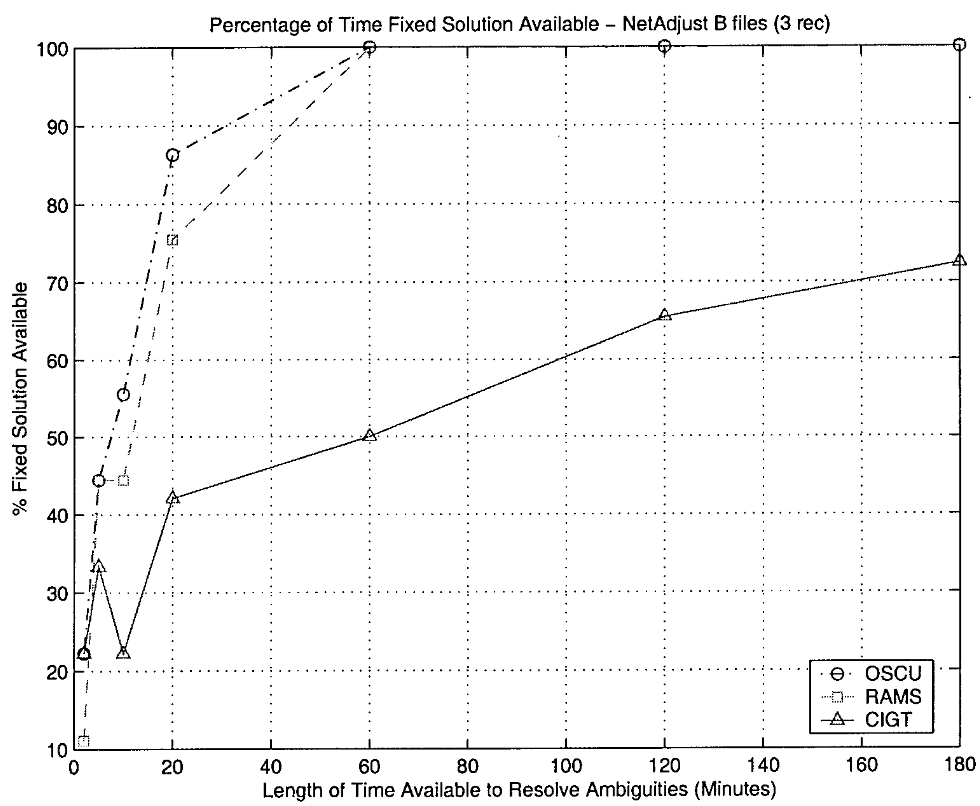

Figure 4-4. Percentage of time a fixed ambiguity solution was available in the NetAdjust corrected B files using three reference receivers

4.4. *Virtual reference receiver results*

For all four cases (raw, 3, 4, and 5 receivers) the virtual reference receiver software was applied to the appropriate B files. For each case, four different virtual reference receiver orders were run, since the measurements used by the virtual reference receiver software are dependent on the order that the B files are fed to the program. The naming convention was rotated in the following manner, CORS (CIGT-OSCU-RAMS-STAL), ORSC, RSCO, and SCOR. Results of creating a virtual reference receiver using the raw B files are shown in Figure 4-5. The 3, 4, and 5 receiver cases only shows three lines. As stated before, the STAL measurements were erroneous. This was proven again when using the virtual reference receiver to create any SCOR ordered B file. Although the B file was produced, AOS would not process the file for 3, 4, and 5 receiver cases.

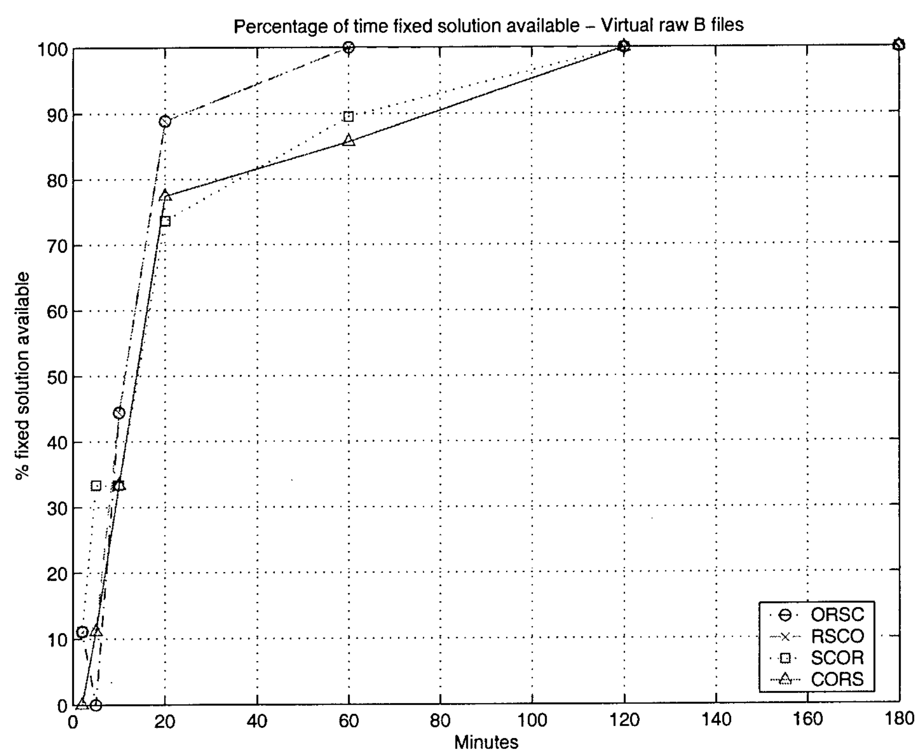

Figure 4-5. Percentage of time a fixed ambiguity solution was available for the raw B files with the virtual reference receiver software applied

The results were surprisingly good, considering that no measurement corrections were applied. The orders where OSCU and RAMS were first (ORSC and RSCO) produced the best (virtually identical) results. Although the remaining orders were approximately 10% worse, their results were still promising considering only the raw B files were used.

The results from the NetAdjust-corrected 5-receiver case in Figure 4-6 were expected to be the best of the four cases. However, only the ORSC order outperformed the raw file. RSCO and CORS performed similarly, except for the CORS 20 minute point. Note that when raw measurements are used, relative positioning errors between reference receivers are not significant like they are in the NetAdjust cases. The fact that NetAdjust actually made the results worse in some cases may indicate that the errors in the relative positioning between reference receivers may have adversely affected NetAdjust results.

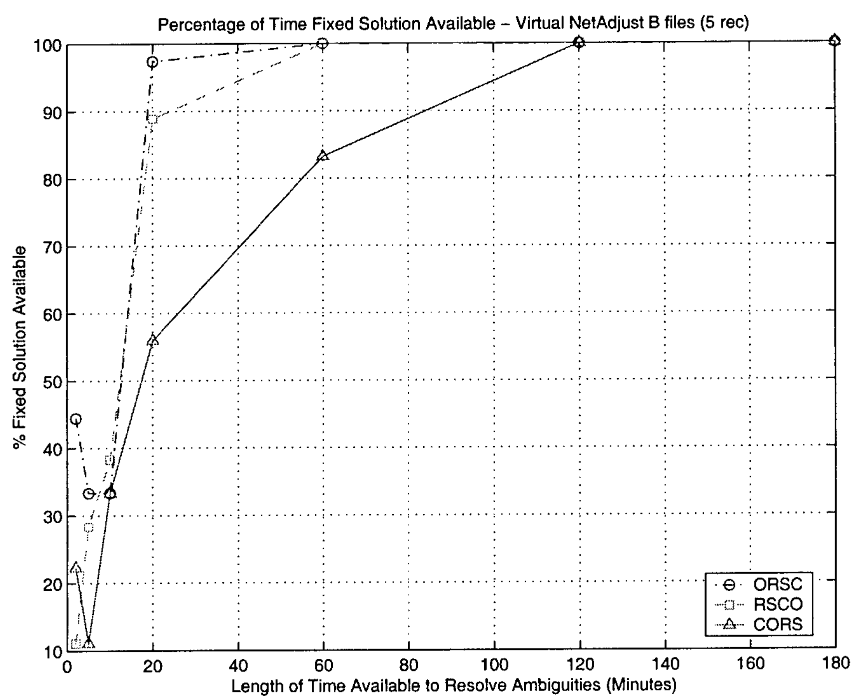

Figure 4-6. Percentage of time a fixed ambiguity solution was available in the NetAdjust-corrected 5-receiver case with the virtual receiver software applied

Figure 4-7 shows the NetAdjust and virtual receiver results for the 4-receiver case. These results were as expected when compared to the 5-receiver case. The performance for all cases decreased.

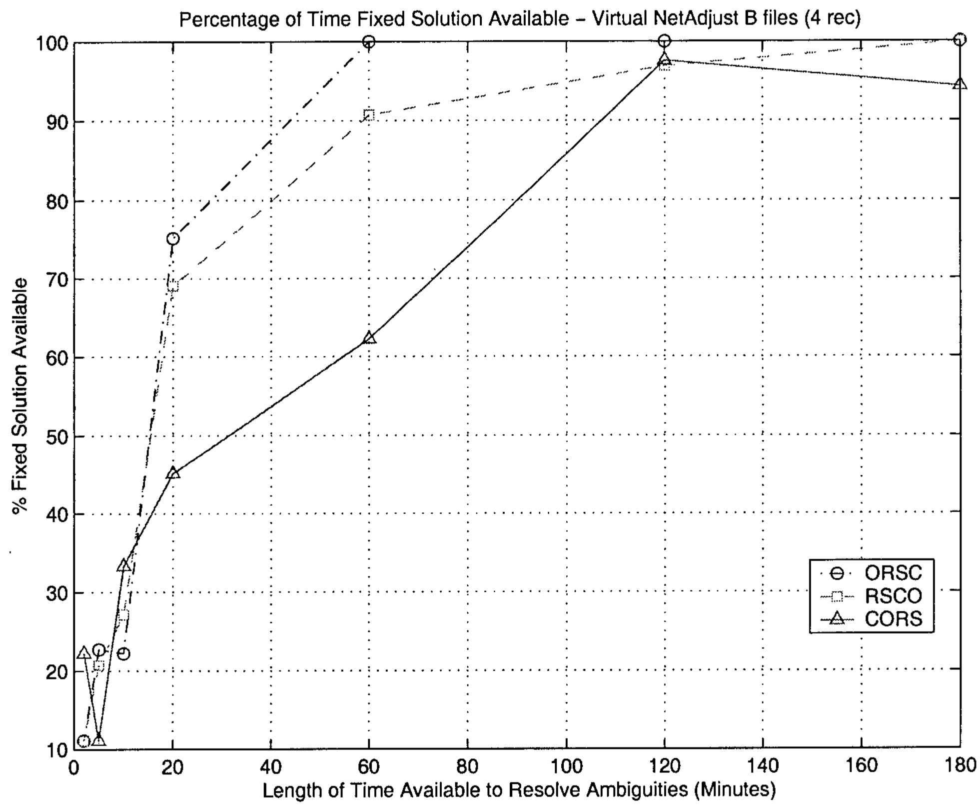

Figure 4-7. Percentage of time a fixed ambiguity solution was available in the NetAdjust-corrected 4-receiver case with virtual reference receiver software applied

The results for the 3-receiver case (with WOOD and STAL removed) were expected to be lower than the 4-receiver case. The results turned out nothing like expected, as shown in Figure 4-8. Every point in every order, with the exception of RCO for 20 minutes, outperformed the 4-receiver case. The results for the 3-receiver ORC order mimicked the ORSC 5-receiver performance, and the rest of the 3-receiver results were very comparable to their 5-receiver partners after 60 minutes. The removal of STAL from the NetAdjust-corrected measurements clearly benefited the virtual receiver

performance, again indicating problems with the STAL measurements, bad STAL coordinates, or both.

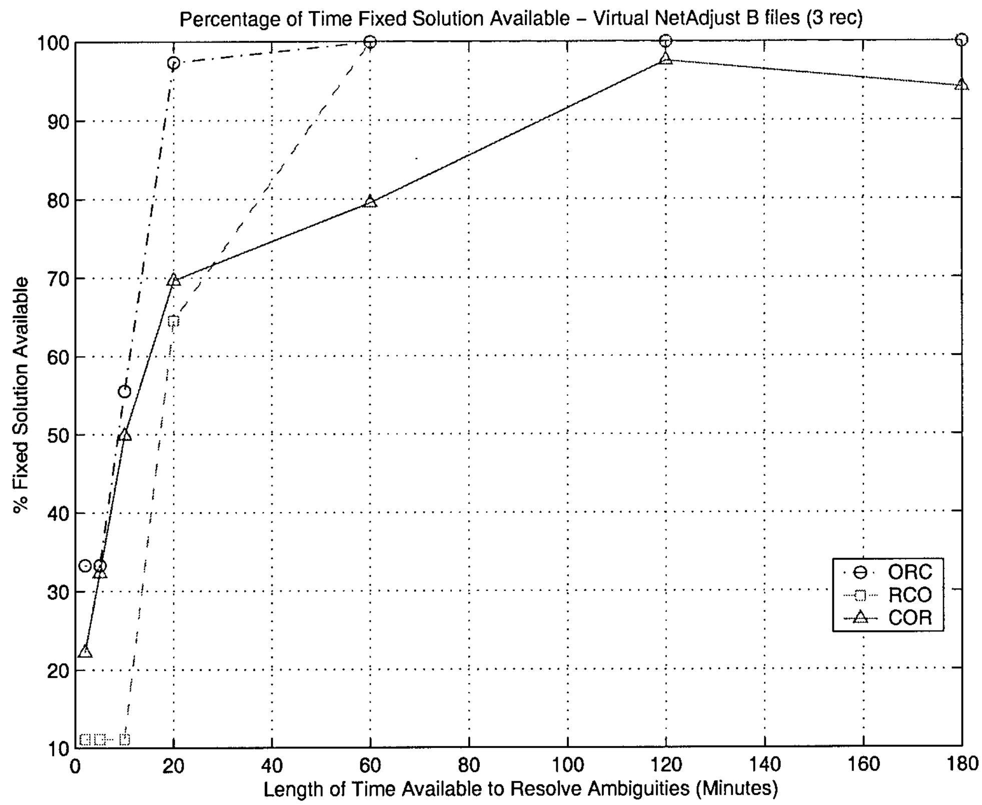

Figure 4-8. Percentage of time a fixed ambiguity solution was available in the NetAdjust-corrected 3-receiver case with the virtual receiver software applied

4.5. Comparison of results for individual reference receivers

Each of the receivers was examined individually to gain further insight into the performance of NetAdjust. Figure 4-9 and Figure 4-10 compare the results from the raw and NetAdjust-corrected 3, 4, and 5-receiver cases for the OSCU and RAMS kinematic baselines. These two receivers have complete and accurate sets of integer ambiguities, as reflected in the percentage of time a fixed solution is available across the four cases. The 5-receiver case performs the best, followed by the 4-receiver case, then the 3-receiver

case, and finally the raw case. These were the results expected for all the baselines, but only occurred with the receivers that have the shortest baseline lengths.

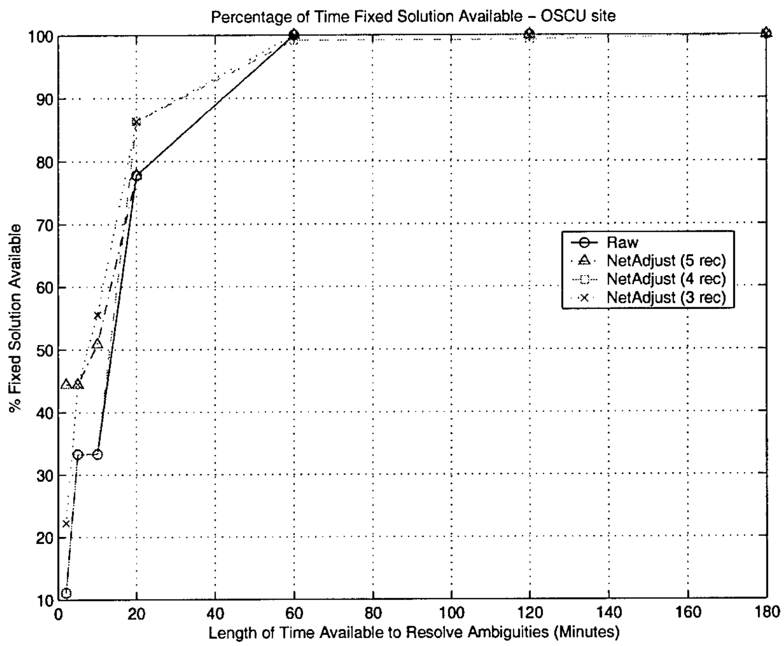

Figure 4-9. Percentage of time a fixed ambiguity solution was available for OSCU

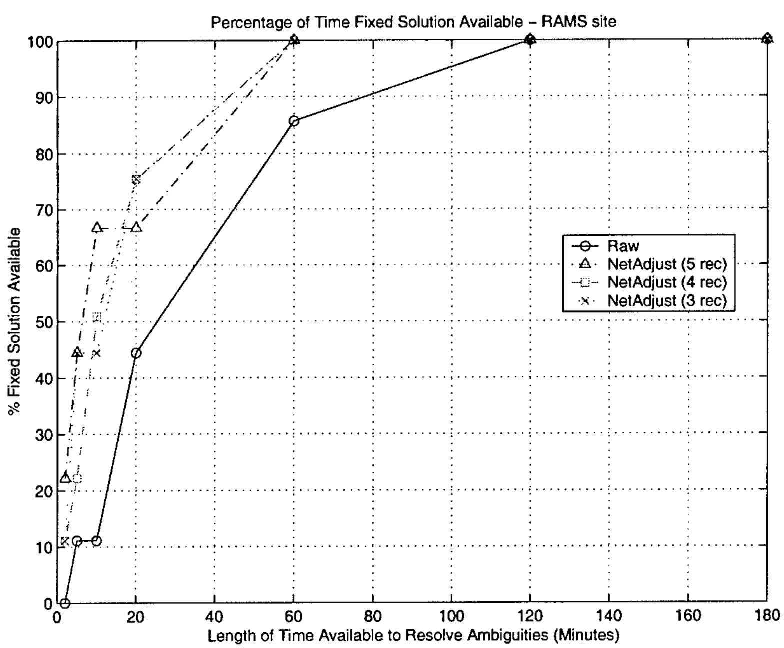

Figure 4-10. Percentage of time a fixed ambiguity solution was available for RAMS

STAL and CIGT, the receivers with longer baseline lengths, unfortunately did not exhibit the same performance. The two receivers were both at the fringes of the network - STAL to the Northwest, and CIGT to the Southeast. This alone does not explain the amount of deviation in the results for STAL, however. The plots in Figure 4-11 indicate that the ambiguity files used by NetAdjust to attempt to correct the raw measurements possess some flaws. This is inferred by noting that the NetAdjust percentages increase up to the 2-hour point, but drop down at the 3-hour point for two of the three cases.

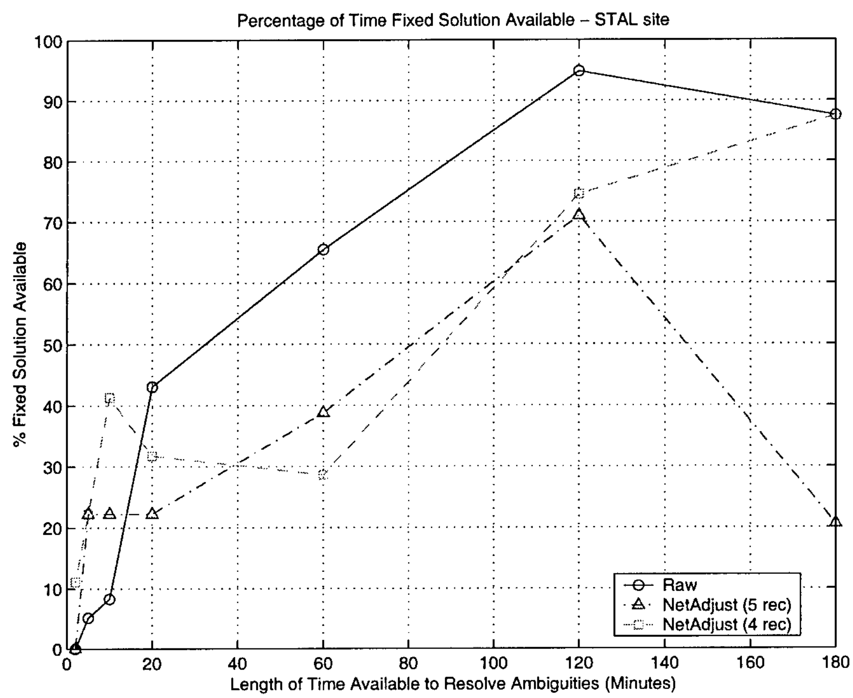

Figure 4-11. Percentage of time a fixed ambiguity solution was available for the three cases where STAL results could be determined

While CIGT performance was superior to STAL, there were still some definite problems. The problems can be attributed to position errors between CIGT and other receivers in the network and to a combination of bad measurements and incorrect integer

ambiguities. Like STAL, CIGT showed a marked improvement in performance when WOOD was removed from the network (see Figure 4-12).

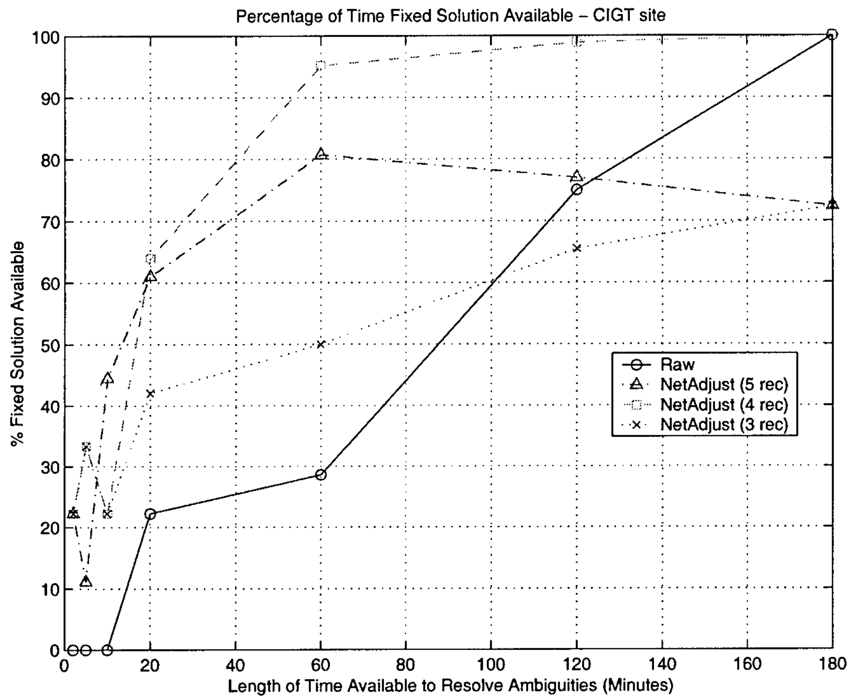

Figure 4-12. Percentage of time a fixed ambiguity solution was available for CIGT

4.6. Comparison of results for virtual receiver cases

The performance of the virtual receiver software displayed superior results in most cases and more importantly, exhibited greater consistency between the different cases. The best performance was obtained when a short baseline receiver was placed first in the ordering of the receivers fed to the software. This was expected since most of the measurements used for the virtual receiver would come from the short baseline receiver, which displayed the best performance in the previous cases. The ORSC order, which had the two shortest baseline receivers first (OSCU and RAMS), displayed the best results of the different orderings processed (see Figure 4-13). While the 5-receiver case displayed the best results, the 3-receiver case closely duplicated the 5-receiver results, especially for

average observation times of 20 minutes or greater. The 4-receiver case was the only deviant from the expected results. Its performance may also be attributed to position errors between the receivers in the network.

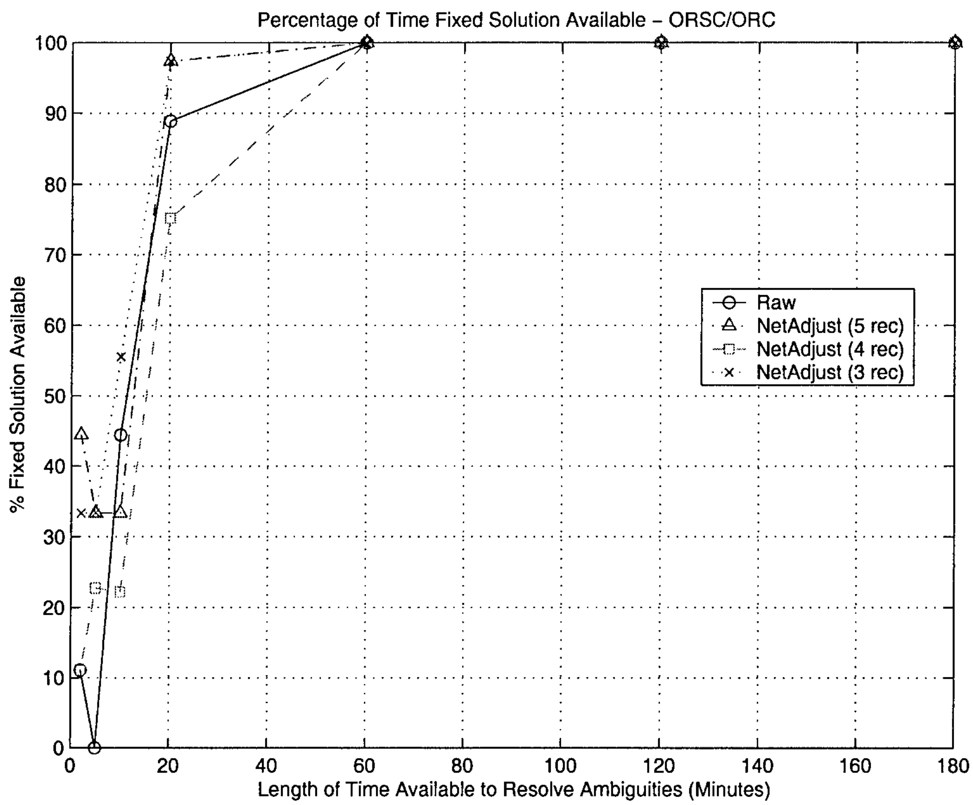

Figure 4-13. Percentage of time a fixed ambiguity solution was available for virtual receiver cases using the ORSC order

Figure 4-14 and Figure 4-15 verified that the performance primarily hinged on the measurements from the first receiver in an order. The order with RAMS first (RSCO) displayed excellent results, while the CORS order with CIGT first did not.

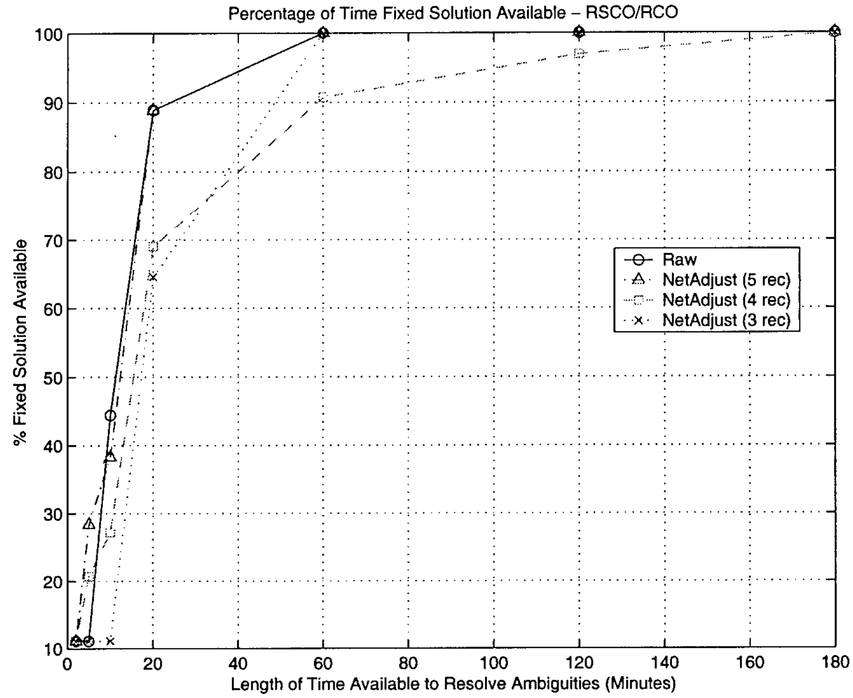

Figure 4-14. Percentage of time a fixed ambiguity solution was available for virtual receiver cases using the RSCO order

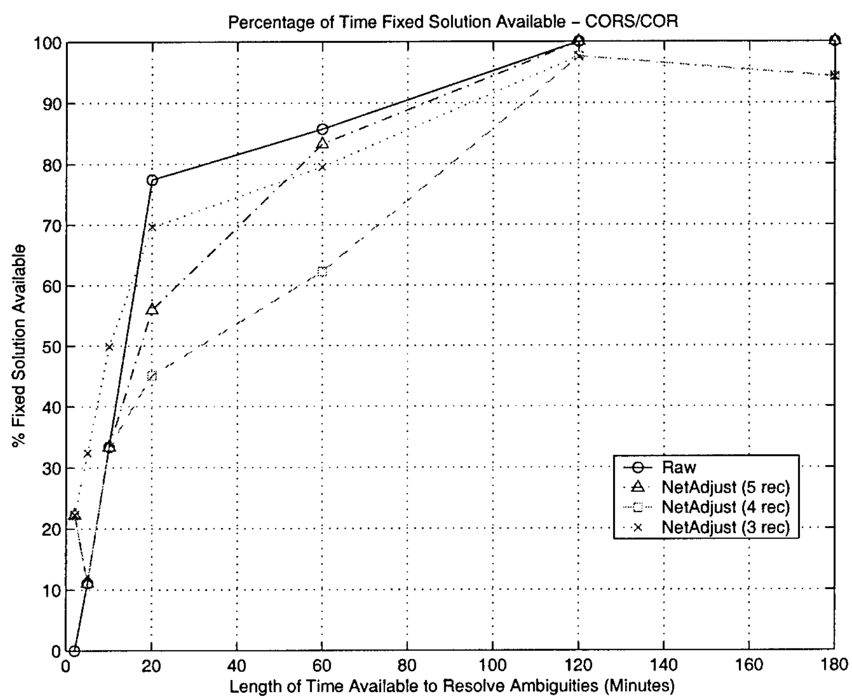

Figure 4-15. Percentage of time a fixed ambiguity solution was available for virtual receiver cases using the CORS order

Note that in both orders the 4-receiver case displayed the worst results. Also note that in the CORS order the raw measurement case displayed the best results. This points again to the receiver position errors.

There is a concern about the current implementation of the virtual receiver software, which will cause an apparent cycle-slip when switching from one receiver as the measurement source to another receiver. At approximately 16:31 GMT, one epoch had a change in the integer ambiguity, but the AOS software did not catch it. The effect of this anomaly was an exceptionally long baseline for one time epoch shown in Figure 4-16. The impact is erroneous data will be utilized by the virtual reference receiver, causing errors in both the receiver coordinates and in any differential baselines.

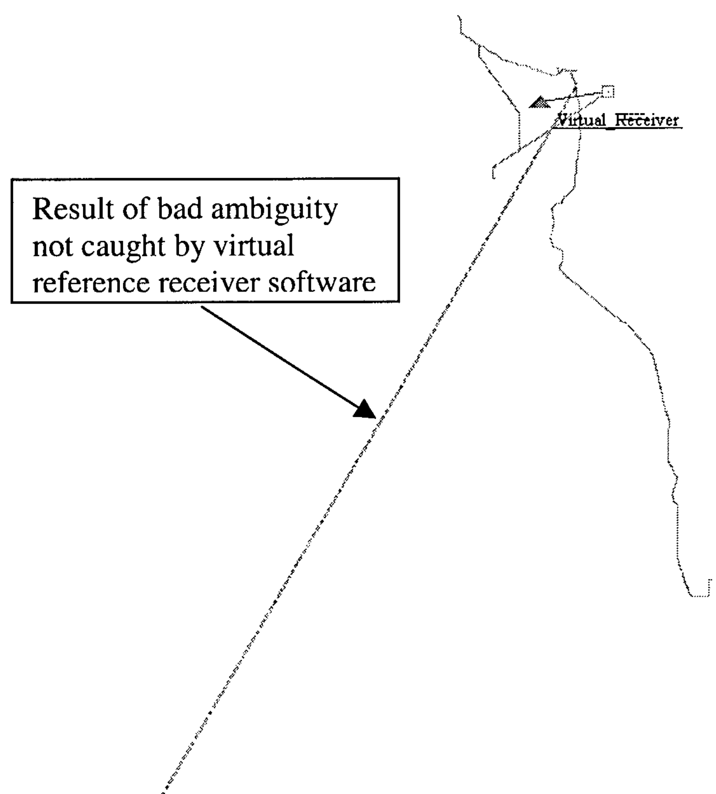

Figure 4-16. Incorrect trajectory generated from NetAdjust-corrected measurements by virtual reference receiver software

4.7. Summary

Several trends were present through all of the cases analyzed. The measurements for the STAL receiver clearly possessed some erroneous data. These errors were traced back to integer ambiguities incorrectly obtained from AOS during a period of multiple cycle slips in the raw STAL B file. Measurements for the OSCU and RAMS receivers performed admirably in all cases. The CIGT receiver measurements performed inconsistently and were the most affected when a reference receiver was added or deleted from the network. This directly supports the hypothesis of errors within reference receiver coordinates. Results in general were unreliable for observation times under 20 minutes. The greatest improvement in the percentage of time a fixed solution was available occurred when increasing the observation time from 10 to 20 minutes. The percentages increased from an average of 22% for the 3-receiver NetAdjust case to 35% for the raw case.

Baseline length played a significant role in the percentage of time a fixed solution was available. Shorter baselines outperformed longer baselines in all cases. When creating a virtual reference receiver from a network of receiver measurement files, using the receivers with shorter baselines early in the order yielded much better performance.

5. Conclusions & Recommendations

5.1. Conclusions

The goal of this research has been an evaluation of an established method of using a reference receiver network to improve positioning accuracy. It has also demonstrated a method of creating a virtual reference receiver. Based on the results obtained, the virtual reference receiver method using NetAdjust-corrected measurements outperformed the original and NetAdjust-corrected measurement file results. This basic result is not what would normally be expected, and it points to several important insights that have been gained from this research.

The first and most important insight is that it is critical to obtain accurate coordinates for the reference receivers. In several cases, such as the improvement in CIGT and STAL performance after the removal of WOOD from the network, it became apparent that an error in relative positioning between reference receivers was present. An assumption was made in this thesis (as required by NetAdjust) that the reference receiver coordinates were without error, although the network misclosures (given in Table 3-1) showed otherwise.

Secondly, the results show that a complete and accurate set of integer ambiguities must be obtained to take full advantage of NetAdjust and the virtual reference receiver concept. The ambiguities are not as critical as the receiver coordinates since previously recorded NetAdjust results [2] increased performance even with only 80% to 90% of the ambiguities resolved between reference receivers. However, it was shown repeatedly through the results that receivers that possessed a complete and accurate set of integer ambiguities had superior performance to those that did not.

The importance of baseline length must be mentioned as well. The receivers with the shortest baselines were also those that had a complete set of ambiguities. Shorter baselines outperformed the longer baselines in all cases. It was also determined that having a shorter baseline receiver first in the virtual reference receiver method order yielded improved performance.

The calculation of the integer ambiguities between reference receivers also weighs heavily in the results of this research. The method of extracting the integer ambiguities from AOS reports had a number of problems. A lack of knowledge and documentation of how the internal software ambiguity resolution algorithms work was at the forefront of these problems. For long baselines, the AOS software was only able to resolve L1 ambiguities. This is curious, because widelane ambiguities are the easiest to determine over long baselines, due to the longer wavelength relative to single-frequency (L1 or L2) ambiguities. If L1 integer ambiguities could be determined, then the algorithm should have been able to resolve and output L2 and Widelane ambiguities in their reports. For cases in which more than two cycle slips were experienced, the software was inconsistent in reporting results in a way that could be recognized and extracted by the custom-generated MATLAB® script file. This greatly complicated the integer ambiguity extraction process and led to anomalies in the results.

One of the most surprising results of this evaluation was the performance of the raw B files with the virtual reference receiver software. The results are very consistent across the different orders used, indicating an independence from baseline length. This is extremely useful, considering that the output of NetAdjust-corrected measurements may

vary depending on the accuracy of the reference receiver coordinates and the quality of their measurements.

The NetAdjust-corrected measurements should provide the best results if a complete, correct set of ambiguities can be obtained from the reference receiver network, and receiver positions are precisely known. Erroneous measurements dictated some unpredictable results that require further research to resolve.

The virtual reference receiver software worked very well and would be an excellent tool to improve the percentage of time a fixed solution was available, especially for test conditions where the reference receivers are more than 30 km away. Another observation in the research was that results in general were unreliable for observation times under 20 minutes in all cases. The greatest improvement in the percentage of time a fixed solution was available occurred when increasing the observation time from 10 to 20 minutes. The percentages increased from an average of 22% for the 3-receiver NetAdjust case to 35% for the raw case. Further improvements were observed as the observation time increased, but the largest percentage of improvement occurred from 10 to 20 minutes.

5.2. Recommendations for Future Work

Although problems associated with the measurements and ambiguities did not permit any firm conclusions to be made, it is recommended that a network of reference receivers be installed across the WSMR. The benefits of possessing a reference receiver network are numerous. First, a reference receiver with accurate coordinates will be present in key test locations at all times to perform single reference DGPS calculations. Secondly, a reference receiver network provides the ability to test the accuracy of state-of-the-art GPS technology such as GPS/INS integration for munitions. Once the network is installed, an

additional advancement would be to establish an active transmission of DGPS corrections across the range for use by any government program for real-time testing and tracking purposes. Most importantly, it would keep the 746th TS at the forefront of emerging GPS technology and give personnel experience with DGPS techniques that would enable them to address and solve the navigation requirements for the next generation of Air Force weapon systems.

Custom-designed ambiguity resolution software may not provide the same user interface as AOS, but it would allow more flexibility in overcoming problems resolving multiple cycle slips. Another option would be persuading the software vendor to make custom changes to the AOS interface to allow more automation and flexibility in obtaining integer ambiguities. Based on this research, it is recommended to contact the Magellan Corporation to explore the feasibility of customizing the AOS software. The exchange of knowledge would benefit both organizations. Magellan would gain insight into customer requirements for subsequent releases of AOS, and the 746th TS would gain the software technology to yield reliable and accurate determination of the information required to implement the NetAdjust and virtual reference receiver methods.

It is also recommended that a comprehensive sensitivity analysis be performed to quantify the accuracy requirements for reference receiver coordinates. The results of the analysis would demonstrate the tradeoff in accuracy between using fixed reference receivers or temporary reference receivers set up for individual tests.

The next step in establishing the feasibility of implementing the NetAdjust method along with a reference receiver network is to accomplish another evaluation. This evaluation would use accurate reference receiver coordinates calculated from a 24-hour

observation period and use the mobile trajectory of the C-12J aircraft used by the 746th TS for test missions.

Appendix A. AOS Processing Checklist

1. Open AOS
2. Set system to WGS-84
3. Insert Ashtech B-files for all receivers into project
   3.1. Check if read as Static or Kinematic file by AOS. If Kinematic, change to Static unless it's the mobile receiver
4. Input coordinates for reference receivers with known coordinates
   4.1. CIGT -1485881.487 -5152018.353 3444641.847
5. Ensure Process – Settings are Static with Lw/Ln >120 km
6. Ensure the Process-Filter-Use OVERALL BEST box is checked
7. If you wish to use precise ephemeris, check box in Process-Settings-Orbit type
8. Save project
9. Process project; if problems, may need to go back and process baselines individually
   9.1. Use Process – Automatic unless some won't process, in that case:
      9.1.1. Change Process – Settings to OTF for short kinematic baselines
      9.1.2. Change Process – Settings to DGPS for long kinematic baselines
10. Conduct biased adjustment, then fix all reference points
11. Save project
12. Save all static and kinematic baseline reports to a distinct directory
    12.1 Select Triple Difference, Ambiguities & Information in Options – Report Settings
    12.2 For kinematic - only the Ambiguity Resolution table should be selected
    12.3 Get rid of Table of Contents
    12.4 Save as *baseline.htm (ie: CIGT_OSCU.htm, or K-CIGT.htm)
    12.5 Open Word and save as *baseline.txt
13. Generate kinematic trajectory file using Trajectory-Properties and the AOS evxyz.m script
    13.1 Open file (ie: ROVR280A.POS) and strip header off, then save
    13.2 Report is generated from rovr280.obs trajectory file properties
14. Go to MATLAB and modify the a.m script file for the baselines where ambiguities are desired
    14.1 Run the script file inside the directory you wish the ambiguity files to be stored
15. The basic ambiguity files are now set for use by the Netamb software, zip together a backup copy and store in a safe place

<u>Obtaining NetAdjust-corrected measurement files and results</u>

1. Open MS_DOS window
2. Run e_to_eph.exe file (e_to_eph <input filename> <output filename>)
   2.1 Use original e-file (e46tga99.280) as input file
   2.2 Copy output file to NetAdjust directory
3. Update site_database.dat file
   3.1 Site ECEF coordinates should be obtained from AOS point properties

4. Edit dd.params file to look for correct file names and directories and to specify output file names and directories
5. Edit the three net_amb.params files (L1, L2 & WL) for names, directories etc
   5.1 Run it - command line is: net_amb net_amb.params
   5.2 The core ambiguity files for NetAdjust are now completed, zip together a backup copy and store in a safe place
6. Edit the na.params file
   6.1 Pick a p0 and a computation point and insert their ECEF coordinates
7. Edit MATLAB amb_val.m file for correct output names (co.dd etc)
8. Run amb_val file to see double difference results as a sanity check
9. Edit the na.bat file for input and output file names
   9.1 Run it

<u>Process to determine NetAdjusted phase positioning % summary</u>

1. Move new NetAdjusted B-files to specified directory
   1.1. Move NetAdjusted raw B-files to separate directory
   1.2. Copy the original E-files to both directories and rename (***n***, ***nr*** convention)
2. Start new project and insert NetAdjusted files and ROVR files into AOS
3. Fix points if necessary (change from kinematic to static etc)
4. Fix all static points to coordinates established in original project (Broadcast.ggs)
5. Change to 120km Lw/Lc, use overall best one solution
6. Process
7. Generate kinematic report
8. Split every B file into one 3-hour file (16:08:20-19:08:20), and nine 20-minute files
   8.1. Do the same processing on each to fill out the results spreadsheet

<u>Running virtual reference receiver software</u>

1. Copy NetAdjusted B and E files, the *.eph file, and site_database.dat to virtual directory
2. Edit naj.params file
   2.1 Input coordinates of desired virtual reference receiver
   2.2 Ensure input and output directories and filenames are correct
3. Run na_join.exe
4. Rename E-files to match the virtual generated B-files
5. Start new AOS project and add virtual B-file and ROVR files into AOS
6. Fix point if necessary (change from kinematic to static etc)
7. Fix reference receiver coordinates to original "known" coordinates
8. Change to 120km Lw/Lc, use overall best one solution
9. Process
10. Generate kinematic report

Appendix B. Acronym List

746th TS	746th Test Squadron
AFIT	Air Force Institute of Technology
AOS	Ashtech Office Suite for Survey
CHAPS	CIGTF High Accuracy Post-processing reference System
CIGTF	Central Inertial Guidance Test Facility
DGPS	Differential Global Positioning System
DOD	Department of Defense
drms	distance root-mean-square
ECEF	Earth-Centered, Earth-Fixed
GMT	Greenwich Mean Time
GPS	Global Positioning System
HTML	Hypertext Markup Language
INS	Inertial Navigation System
MMR	Measurement-minus-range
OTF	On-the-fly
PPS	Precise Positioning Service
PR	Pseudorange
PRN	Pseudorandom Noise
RMS	Root-Mean-Square
SA	Selective Availability
SPS	Standard Positioning Service
SV	Satellite Vehicle
TEC	Total electron content
WGS-84	World Geodetic System 1984
WSMR	White Sands Missile Range

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Vita.

Captain Brian L. Bracy hails from Fairfield, California. He graduated in December 1994 from Embry-Riddle Aeronautical University-Prescott Campus with a Bachelor's of Science in Electrical Engineering . After commissioning that same year, he reported to the 6th Space Operations Squadron (6 SOPS) at Offutt AFB, NE. While at the 6 SOPS from April 1995 to August 1998, he played a key role in the launch of Defense Meteorological Satellite Program (DMSP) Flight 14 and in the first handover of a military satellite constellation to a civilian agency. From August 1998 to March 2000, Captain Bracy attended the Air Force Institute of Technology where he was awarded the degree of Masters of Science in Electrical Engineering. He is married to the former Crystal King of Prescott, Arizona and they have four children. Captain Bracy is currently assigned to the 746th Test Squadron, Holloman AFB, NM.

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14. ABSTRACT
New applications for GPS have driven a demand for increased positioning accuracy. The emerging GPS technology particularly affects the test community. The testing equipment and method must provide a solution that is an order of magnitude more precise than the tested equipment to achieve the desired accuracy. Carrier-phase differential GPS methods using a network of reference receivers can provide the centimeter-level accuracy required over a large geographical area. This thesis evaluates the performance of a 5-receiver network over a 50 km x 120 km area of New Mexico, using a GPS network algorithm called NetAdjust. The percentage of time a fixed integer solution was available for a kinematic baseline was investigated for three types of measurements. Results showed that the virtual reference receiver method using NetAdjust-corrected measurements outperformed the raw and NetAdjust-corrected file results. However, these results were only obtained for the shortest baseline receivers. The receivers with longer baselines did not experience the same degree of success, but did lead to several important insights gained from the research. Most importantly, the accuracy of the reference receiver coordinates is critical to the performance of a reference receiver network. Further testing must be accomplished before a full implementation is recommended.

15. SUBJECT TERMS
GPS, Global Positioning System, network, networks, receiver, receivers, reference, virtual, kinematic, NetAdjust, ambiguity, ambiguities, ambiguity resolution, carrier-phase

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